DTU Library

Synthesis

Larsen, Hans Hvidtfeldt; Bindslev, Henrik; Sønderberg Petersen, Leif

Published in:
Risø energy report 9

Publication date:
2010

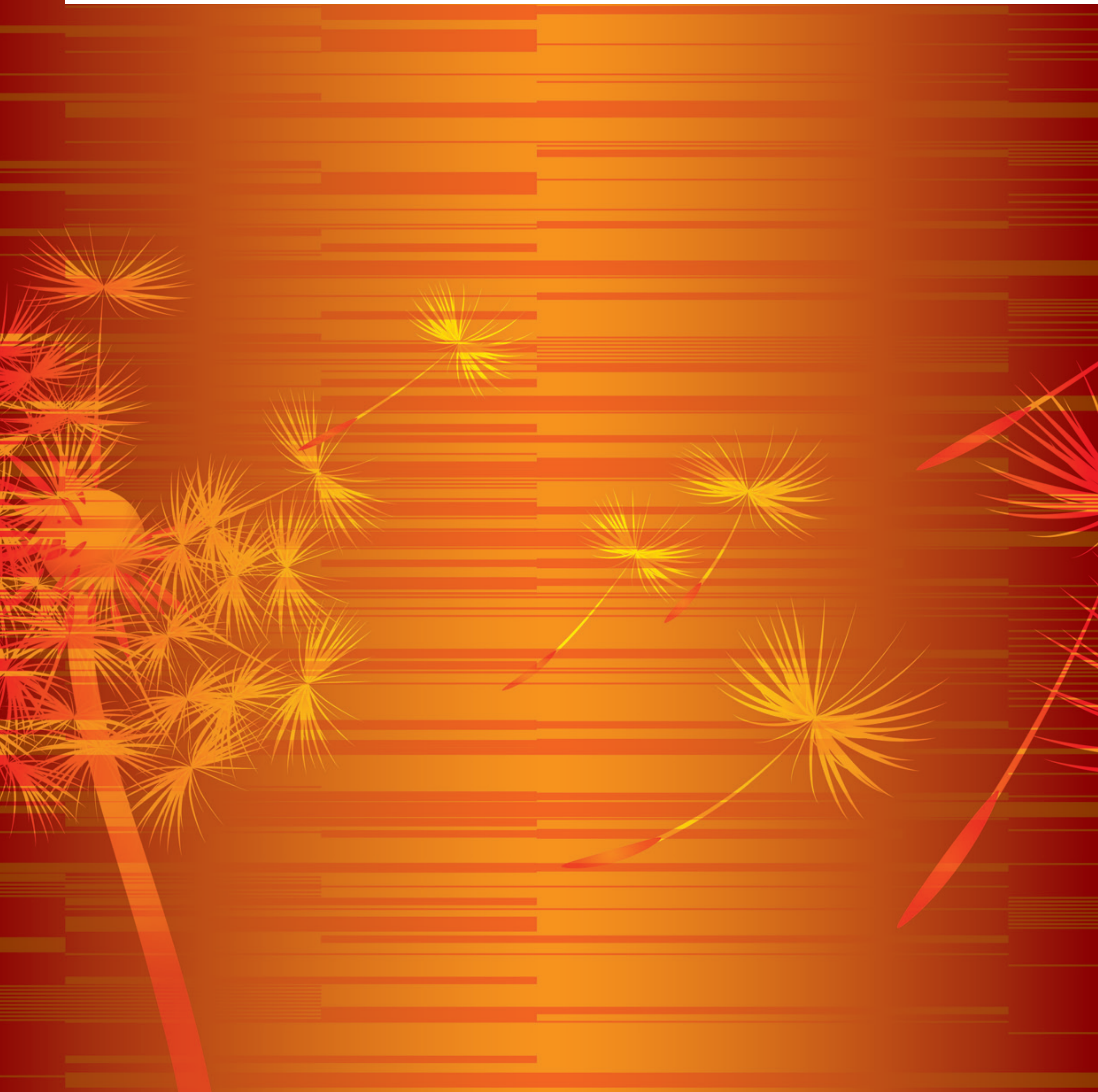
Document Version
Publisher's PDF, also known as Version of record

Risø Energy Report 9

Non-fossil energy technologies in 2050 and beyond

Risø-R-1729(EN) November 2010

Edited by Hans Larsen and Leif Sønderberg Petersen



Risø DTU
National Laboratory for Sustainable Energy

Risø Energy Report 9

Edited by
Hans Larsen and Leif Sønderberg Petersen

Reviewed by
Diana Urge-Vorsatz, Central European University, Hungary
Lars J. Nilsson, Lund University, Sweden

Editorial consultant
Charles Butcher, Science Journalist, UK

Risø-R-1729(EN)

ISBN 978-87-550-3812-7

ISBN 978-87-550-3813-4(Internet)

ISSN 0106-2840

Risø Energy Report 9

Non-fossil energy technologies in 2050 and beyond

Edited by
Hans Larsen and Leif Sønderberg Petersen

Reviewed by
Diana Urge-Vorsatz, Central European University, Hungary
Lars J. Nilsson, Lund University, Sweden

Editorial consultant
Charles Butcher, Science Journalist, UK

Risø-R-1729(EN)

ISBN 978-87-550-3812-7

ISBN 978-87-550-3813-4(Internet)

ISSN 0106-2840

Contents

1
Preface

This Risø Energy Report, the ninth in a series that began in 2002, analyses the long-term outlook for energy technologies in 2050 in a perspective where the dominating role of fossil fuels has been taken over by non-fossil fuels, and CO_2 emissions have been reduced to a minimum.

Against this background, the report addresses issues like:
- How much will today's non-fossil energy technologies have evolved up to 2050?
- Which non-fossil energy technologies can we bring into play in 2050, including emerging technologies?
- What are the implications for the energy system?

Further, Volume 9 analyses other central issues for the future energy supply:
- The role of non-fossil energy technologies in relation to security of supply and sustainability
- System aspects in 2050
- Examples of global and Danish energy scenarios in 2050

The report is based on the latest research results from Risø DTU, together with available international literature and reports.

Hans Larsen and Leif Sønderberg Petersen

Risø National Laboratory for Sustainable Energy,
Technical University of Denmark

2
Summary and main conclusions

Hans Larsen and Leif Sønderberg Petersen, Risø DTU, Denmark

Long-term energy security depends on the continuing availability of fossil fuels and their potential substitution by renewable energy sources. Coal and gas may well dominate the global primary energy supply for the rest of this century if no special effort is made to promote renewables. However, for many countries energy security concerns are accompanied by a preference for renewable options which can reduce their dependence on imported oil and gas, as well as helping to meet environmental policy objectives.

To keep the global mean temperature rise below 2°C we need, according to the IPCC, to reach global stabilisation at 450 ppm CO_2eq, which means that global greenhouse gas (GHG) emissions must be halved by 2050 and in fact reduced even more in the OECD countries.

According to the analyses presented in this report, it will be difficult for the European countries to meet these targets as mitigation options from the energy sector alone do not seem to be sufficient, but have to be supplemented by action from other sectors, for example the agricultural sector.

On the other hand, the Danish case described in this report shows that Denmark stands a good chance of meeting the mitigation goals and of being able to phase out fossil fuels rapidly and thus reduce GHG emissions at the pace needed. Denmark's wind and biomass resources, in particular, would allow the phase-out of fossil fuels from the generation of electricity and heat before 2040. Removing fossil fuels from the transport sector will probably take another 10 years.

Renewable energy technologies

Solar energy can be used to generate heat and electricity all over the world. Our technical ability to exploit this resource has improved dramatically in recent years, and by 2050 the IEA forecasts that the PV and CSP technologies will each produce 11% of the world's electricity.

PV is by nature a distributed generation technology, whereas CSP is a centralised technology, so their deployment will follow very different routes. PV is unique among electricity generation technologies in that its distributed nature allows it to be integrated with human settlements of all sizes, urban or rural.

Since 1970, **wind energy** has grown at spectacular rates, and in the past 25 years global wind energy capacity has doubled every three years. The current wind energy capacity of approximately 160 GW is expected to generate more than 331 TWh in 2010, covering 1.6% of global electricity consumption.

Most of the development effort so far has been dedicated to the evolutionary scale-up and optimisation of the land-based three-bladed standard wind turbines which emerged as commercial products at the beginning of the 1980s.

The coming decade may see new technological advances and further scale-up, leading to more cost-effective, reliable and controllable wind turbines and new offshore and onshore applications, including the introduction of wind power in the built environment. With increased focus on offshore deployment combined with the radically different conditions compared to onshore, it is likely that completely new concepts will emerge, such as the vertical-axis turbine currently being developed at Risø DTU. Wind energy has the potential to play a major role in tomorrow's energy supply, cost-effectively covering 30-50% of our electricity consumption.

Hydropower is a mature technology close to the limit of efficiency, in which most components have been tested and optimised over many years.

Wave energy can be seen as stored wind energy, and could therefore form an interesting partnership with wind energy. Globally, the potential for wave power is at least 10% of total electricity consumption, or more if we tolerate higher prices. An ambitious yet realistic goal for Danish wave power by 2050 could be around 5% of electricity consumption.

Biomass presently covers approximately 10% of the world's energy consumption. A realistic estimate of the total sustainable biomass potential in 2050 is 200-500 EJ/yr covering up to half of the world's energy needs in 2050.

A large proportion of biomass will probably still be in the form of wood for direct burning in less developed areas of the world. Biomass plays a special role as an easily storable form of energy, in CHP systems based on sophisticated combustion technologies, and as a source of liquid fuels for transport.

Several technologies are currently being developed with a view to improving biomass use, and these will help to make bioenergy competitive when oil prices increase. Biomass is a limited resource, and increases in biomass production should preferably not compete with the food supply.

Geothermal energy is used in two ways: At least 24 countries produce electricity from geothermal energy, while 76 countries use geothermal energy directly for heating and cooling. In 2008, the global production of geothermal heat was 0.2 EJ, with 10 GW of installed baseload electricity production capacity.
The potential for the future is huge. According to estimates by the International Energy Agency, the most probable potential for the global geothermal resource is approximately 200 EJ/yr, including 65 EJ/yr from electricity production.

In Denmark, the potential for geothermal energy is substantial since suitable aquifers are available, and the technology is an excellent match for the district heating systems already widely used. Geothermal energy is therefore expected to cover a large part of the demand for future district heating. The Greater Copenhagen area has enough geothermal reserves to meet all its needs for heat for thousands of years.

To date, R&D work on **energy storage** has focused on electricity, as electricity storage has an obvious, straightforward and urgent role in the energy market. Many types of electricity storage will be of great importance in the coming decades.

A shift to sustainable energy sources will also require mobile storage technologies for vehicles. Capturing electricity from wind and solar sources in a concentrated form, these will need to deliver driving ranges similar to those of modern gasoline and diesel vehicles.

In future storing energy as hydrocarbons synthesised from hydrogen, made by the electrolysis of water, and carbon dioxide extracted from the atmosphere may become viable. The distribution system for liquid fuels is in place, so synthetic liquid fuels will not require huge investments in new distribution systems.

There is also considerable technical and economic potential for heat storage. Energy storage has enormous technical potential, and it is likely to appear in many different guises among the building blocks of a future sustainable energy system. However, the costs associated with storing energy are often considerable and sometimes prohibitive.

Nuclear fission is a proven technology, but its exploitation has grown only slowly in the past 30 years. However, the need for an energy supply with low fossil fuel dependence and low greenhouse gas emissions has led to renewed interest in nuclear energy. Many countries now plan to adopt or expand their use of nuclear fission. In total, nuclear provides 14% of the world's electricity consumption, though this figure has fallen slightly in recent years.

USA expects a nuclear renaissance, and China, India and Russia have even more ambitious plans for expanding nuclear power by 2030 through the installation of 100, 60 and 20 GWe, respectively. Based on existing plans, world nuclear capacity may therefore increase from its present 340 GWe to more than 1,000 GWe in 2050, increasing nuclear's share of the electricity supply to 20%. The next generation of nuclear energy systems, Generation IV, may be deployed from 2040 onwards. Generation IV systems include fast-neutron breeder reactors, allowing for a much improved utilisation of uranium and thorium resources and a reduction of the radioactive waste. The reactors have higher operating temperatures, which opens up for new applications of nuclear energy, such as the production of liquid chemical fuels and thermo-chemical hydrogen production. Fusion research is now taking the next step with the construction of ITER. Expected to start operating in 2020, ITER will demonstrate self-sustaining controlled fusion for the first time by 2026. Building on experience gained from ITER, plans are to build the future DEMO facility in 2030-2040 and for it to operate during 2040-2050, generating several hundreds of megawatts for extended periods of time. DEMO will also test and qualify key components under realistic operating conditions. If everything goes according to plan, the first commercial fusion power plant will then be commissioned by 2050.

Carbon capture and storage (CCS) can be used on large point sources based on fossil fuels such as power plants and industrial furnaces. The technology can be retrofitted at existing combustion plants without major changes, but running costs are rather high.

The main cost of CCS relates to the CO_2 capture stage, in terms of both its capital cost and the loss in efficiency at the power plant to which it is fitted, which is to the order of 24-40%.

To improve the chances of meeting the targets for CO_2 reduction, CCS should be used worldwide, and the building of full-scale demonstration plants must be accelerated to drive down costs. Proven fossil fuel reserves, especially coal, will last far beyond this century. With CCS we can continue to burn fossil fuels even in a carbon-neutral future. Later, CCS can even be used with biomass-fired power plants to create net negative CO_2 emissions.

Denmark still has a good chance of exploiting CCS, with plenty of geological storage capacity both onshore and offshore. With an increase in wind energy, Danish coal-fired power plants will provide the baseload and can operate flexibly even with CCS.

System aspects

It will not be possible to develop the energy systems of the future simply by improving the components of existing systems. Instead, we need an integrated approach that will optimise the entire system, from energy production, through conversion to an energy carrier, energy transport and distribution, and efficient end-use.

Similarly, significant reductions in primary energy consumption will not be reached through evolutionary development of existing systems. This will require paradigm shifts and revolutionary changes, such as the automatic adaptation of consumption to match the instantaneous availability of all forms of energy.

There is also a need for a smart grid which will link production and end-use at the local level. End-users must help to maintain balance in the future energy system. New end-use technologies have to be widely introduced, including highly insulated, almost self-sufficient houses, smart electronic equipment, energy storage and local energy supplies such as heat pumps. Information and communications technology (ICT) will be very important to the successful integration of renewables in the grid.

Electric supergrids based on high-voltage direct current (HVDC) technology are promising because they offer the controllability needed to handle wind power effectively as well as efficient transport of electricity over long distances, even between different synchronous zones. Compared to other energy distribution systems, power grids are particularly vulnerable to disturbances and accidents. Today, the welfare gains are too insignificant to motivate end-users, because in most countries the production cost of electricity is small compared to the fixed added taxes and tariffs. Switching to value added taxes, grid payments which vary according to the grid load, and variable tariffs and taxes could stimulate flexible demand and "demand shifting".

Main conclusions

By 2050, the sum of the potential of all the low-carbon energy sources exceeds the expected demand. The challenge for a sustainable global energy system with low CO_2 emissions by 2050 is therefore to utilise this potential in the energy system to the extent that it can be done in an economically attractive way.

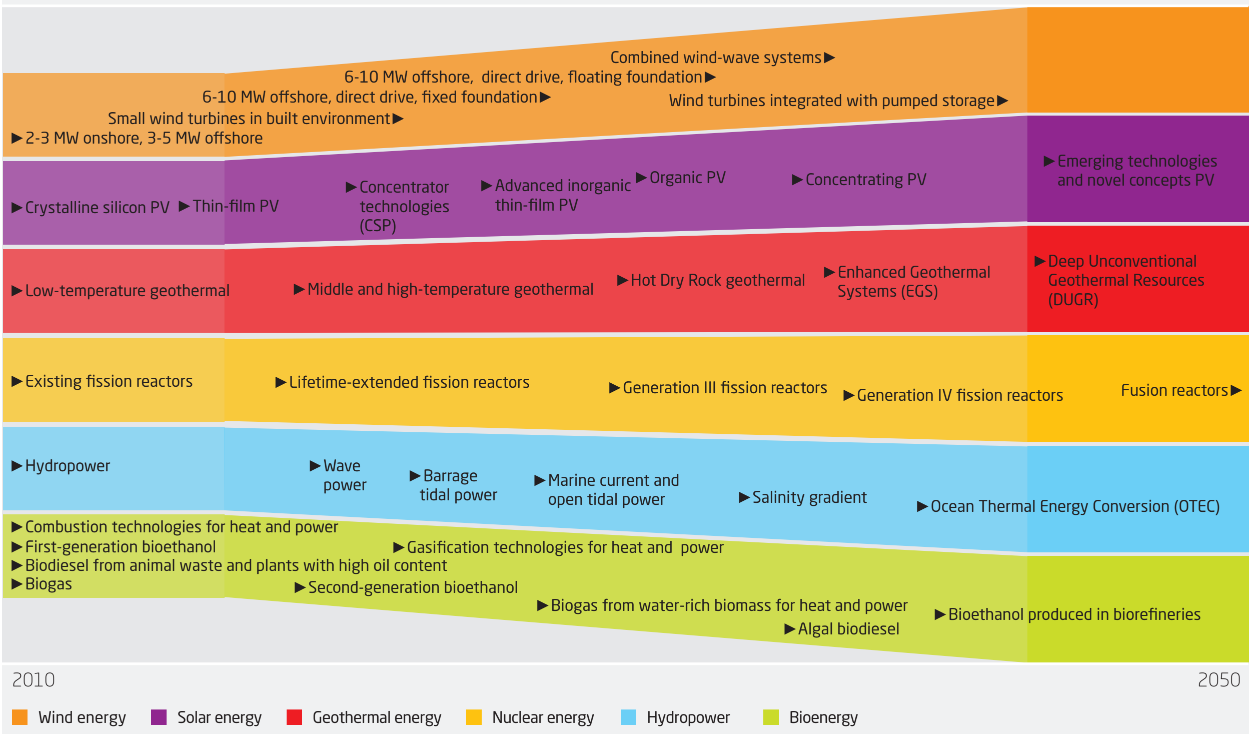
It will not be possible to develop the energy systems of the future simply by improving the components of existing systems. Instead, we need an integrated process that will optimise the entire system, from energy production, through conversion to an energy carrier, energy transport and distribution, and efficient end-use.

Similarly, significant reductions in primary energy consumption will not be reached through evolutionary development of existing systems. This will require paradigm shifts and revolutionary changes, such as the automatic adaptation of consumption to match the instantaneous availability of all forms of energy.

Several energy supply technologies with low or even zero GHG emissions are already available on the market or will be commercialised in the decades ahead.

A future intelligent power system requires investment now, since uncertainty among investors is already hindering progress towards a higher share of renewable energy. If we do not make this investment, future generations may look back in disbelief that for so long we tolerated an antiquated energy system without putting in place the improvements that were already possible.

Developments in non-fossil energy technologies 2010 - 2050



3
The global energy scene in 2050

Kirsten Halsnæs, Risø DTU, Denmark; P.R. Shukla, Indian Institute of Management, India;
John M. Christensen, UNEP Risø Centre, Risø DTU, Denmark

Introduction

This chapter considers scenarios for future energy systems over the next 40-100 years, focusing on how policy on energy security and climate change can influence the penetration of renewable energy. The scenarios discussed here address energy security in terms of the availability of fossil fuel resources and potential renewable substitutes.

The studies reviewed expect fossil fuels, in particular coal and gas, to remain sufficiently plentiful and cheap that they will continue to dominate global primary energy consumption for the rest of this century if no special efforts are made to promote renewable energy and to support climate change mitigation.

Working against this, however, is the assumption that renewables can help many countries to both increase their energy security, by reducing their dependence on scarce imported oil, and to meet environmental priorities. Policies for stabilising climate change share some common ground with policies for increasing energy security in terms of the energy options they recommend. When countries depend on imports, fossil fuel consumption, for instance, will tend to decrease in both cases, with a consequent increase in the use of renewable energy. However, carbon capture and storage (CCS) by coal, oil, and gas power plants can help to meet climate change goals, yet would compete with renewable energy as a climate change mitigation option and could even reduce energy security by increasing the demand for fossil fuels.

The following section presents the results of three global energy studies: the IEA's Energy Technology Perspectives (IEA 2008), scenarios based on the IMAGE model by the Netherlands Environmental Assessment Agency (Rao et al. 2008), and scenarios based on the MiniCam model by Battelle in the USA (US 2007). After this we discuss a case study for India based on the ANSWER-MARKAL model (Shukla et al. 2010).

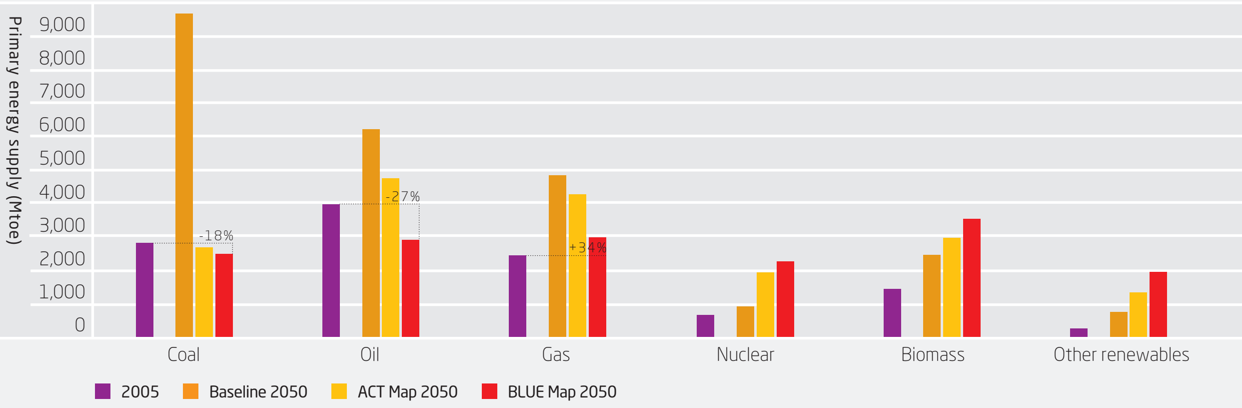
Global scenarios

The IEA Energy Technology Perspectives (ETP) (IEA 2008) covers the 2005-2050 period (Figure 1) in three scenarios:

- a baseline case;
- ACT Map, which includes climate-friendly technologies, both existing and advanced; and
- BLUE Map, which assumes more rapid changes in the energy system designed to stabilise global warming at 2°C.

Our focus here is on the BLUE Map scenario, whose climate policy goals are comparable with those of the other studies discussed in this chapter.

Figure 1
World primary energy sources under the ETP baseline, ACT Map and BLUE Map scenarios, 2050



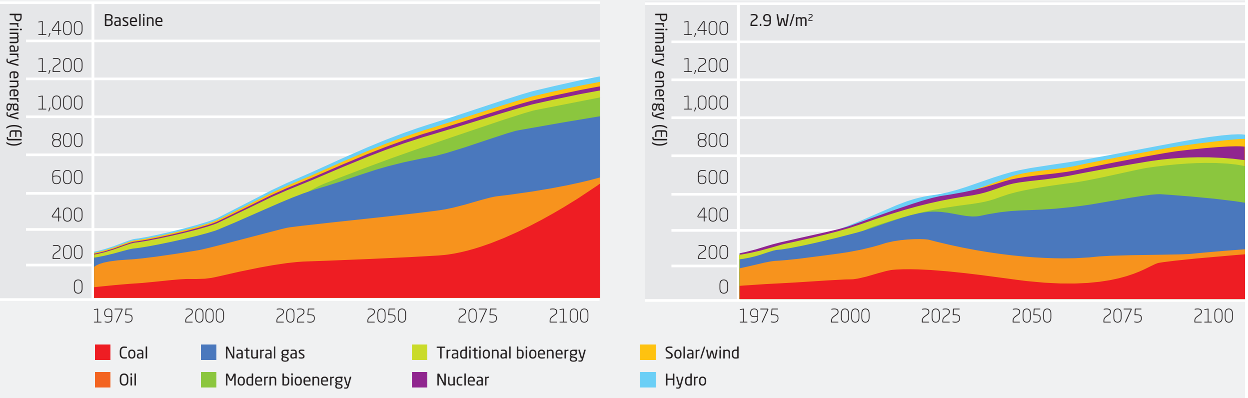
In the BLUE Map scenario, global CO_2 emissions from the energy sector have in 2050 fallen to 50% of their 2005 level, corresponding to the low end of the reductions required to stabilise global warming at 2°C according to the IPCC, 2007. Out of this reduction, energy efficiency improvements account for as much as 36% in the ACT Map and 44% in the BLUE Map of emission reductions in 2050.

The CO_2 emission reduction also requires major changes in fuel composition compared with the baseline scenario. In the BLUE Map scenario, fossil fuel consumption falls by 59% by 2050. Renewable energy, especially biomass, increases fast, and by 2050 is almost as large as total oil consumption was in 2005 (around 6,000 Mtoe). However, by 2005 fossil fuels still provide almost 50% of our primary energy, while renewables account for just below 30%, of which biomass makes up two-thirds. In the ETP baseline scenario, for comparison, fossil fuels cover 84% of total primary energy consumption in 2050.

The IMAGE scenarios (Figure 2) cover the period up to 2100. They include two stabilisation scenarios, of which one (the "2.9 W/m² radiative forcing case") is comparable with the target atmospheric GHG concentration set by the ETP scenario and set by the ETP BLUE Map scenario.

slowly at the beginning of the period as depletion leads to higher prices, but this in turn encourages the development of new unconventional resources, causing oil consumption to rise again later in the period. Among non-fossil energy sources, renewables, especially non-biomass, rise faster than nuclear power.

Figure 2
Energy use in the IMAGE baseline and stabilisation scenarios



The IMAGE baseline scenario makes similar predictions to those of ETP: Fossil fuels will contribute about 80% of our primary energy in 2050, a share that will decrease slightly by 2100 as oil reserves are depleted and natural gas is increasingly used for transport as a substitute for oil.

The 2.9 W/m² stabilisation scenario predicts a decrease in energy consumption of about 30% in 2050. Coal consumption is reduced during the first part of the period studied, when coal is used to produce electricity with carbon capture and storage (CCS). In the years up to 2100, coal's share of primary energy rises again, and oil consumption also increases slightly. The increase in oil use is explained as consumption postponed due to relatively high oil prices in the first part of the century. Coal increases its share of primary energy consumption in the last part of the scenario period due to the use of the emerging CCS technology. Renewable energy contributes about 30% of primary energy consumption in 2050 and also in 2100, and bioenergy is very dominant.

Our third set of long-term scenarios are those developed at Battelle by the US Climate Change Science Program (US 2007) using the MiniCam model. One of the three Battelle scenarios is for climate change stabilisation at 2.9 W/m², as in the IMAGE study (Figure 3).

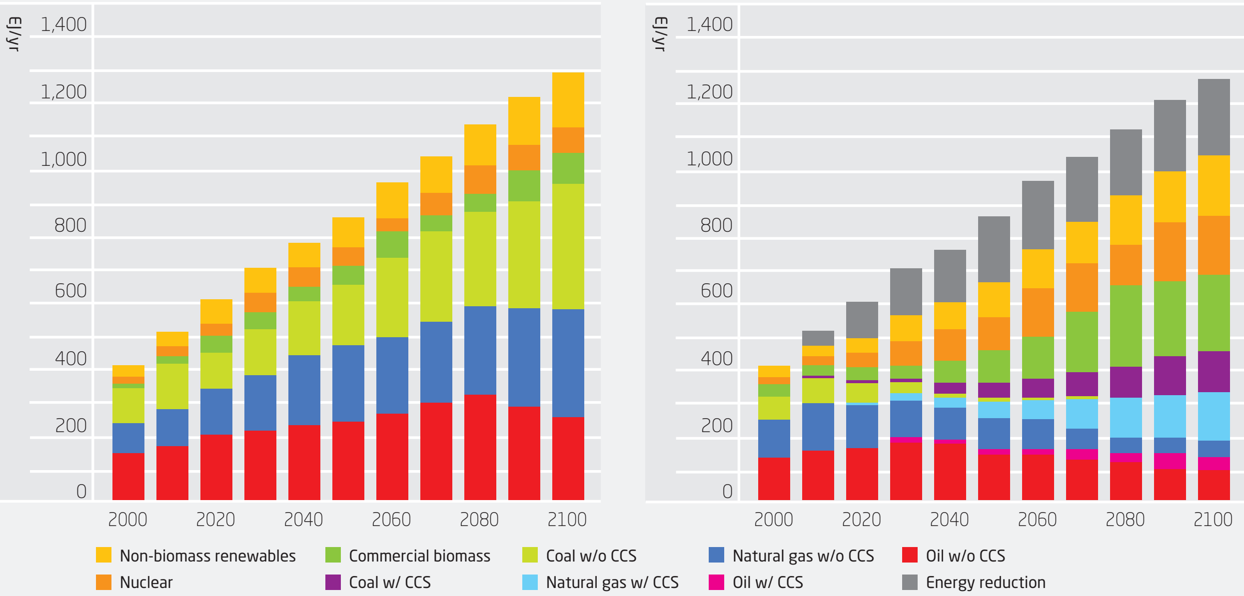
The MiniCam baseline scenario predicts that fossil fuels will contribute about 70% of global primary energy in 2100 and a similar share in 2050. Oil consumption grows relatively

In the stabilisation scenario, by contrast, global gas, oil and coal consumption falls by two-thirds by 2100, and total energy demand falls by about 15%. Nuclear power doubles in size. The greatest increase in renewables is seen in commercial biomass, especially beyond 2050. Non-biomass renewable energy sees only a modest rise compared to the baseline scenario, reflecting an assumption that these energy sources are less cost-effective than CCS, nuclear power and bioenergy. Such results do not need to match exactly what is concluded in assessments of individual technologies, which can be more context-specific and can take other issues into consideration as for example synergies with local environmental goals.

An overall conclusion from this brief comparison of three global modelling studies is that expanding the time horizon from 2050 to 2100 might set a new agenda for energy security issues and also open a new window of opportunity for climate-friendly technologies. Furthermore, it is a commonality that energy efficiency improvements are key to reducing costs and also to generally reducing energy consumption due to limited renewable energy options.

The baseline scenarios of the IMAGE and MiniCam studies foresee increasing possibilities for oil and natural gas in the last part of the 21st century due to the discovery of new resources. This expectation is shared with the recent IEA Energy Technology Perspectives 2010 (ETP 2010). Together with rich coal resources, this will allow fossil fuels to provide

Figure 3
Global primary energy consumption in the MiniCam baseline (left) and stabilisation (right) scenarios



up to 80% of global primary energy in 2100 without really compromising energy security, despite the issue of dependence on imported fuels.

In contrast, the ETP baseline scenario for the period up to 2050 assumes fossil fuels' share to be only about 75% , with a lower consumption of oil and gas in 2050 compared to the IMAGE and MiniCam scenarios. Nuclear power, especially, and renewable energy play more important roles in the ETP study than in the IMAGE and MiniCam studies. One reason for these differences is that the depletion of oil resources and the associated price increases seem to become more acute in the years around 2050, when the ETP study ends. The two longer-term studies assume that new oil and gas resources will be discovered later in the century, though we might consider this rather uncertain.

Climate change stabilisation scenarios for low temperature rise targets based on the ETP, IMAGE and MiniCam studies require large cuts in fossil fuel use, especially coal, but the studies also conclude that adding CCS to coal, oil and gas power plants will allow the continued use of fossil fuels on a large scale. These resources contribute about 50% of global primary energy consumption in 2050 according to the ETP study, about 60% in 2100 in the IMAGE study, and about 40% in 2100 in the MiniCam study. In the stabilisation scenarios of all three studies, nuclear power typically doubles its share. As a result, renewables are expected to cover less than 30% of global primary energy consumption in 2100, or 2050 in the case of the ETP study.

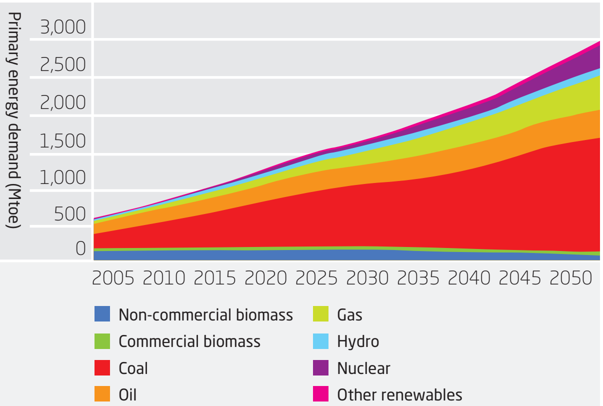
Case study: India

Researchers in India have used the energy sector MARKAL-Answer model to assess the potential for increasing the country's use of renewable energy as part of action to stabilise climate change (Shukla et al. 2010). Figure 4 shows the trends in primary energy consumption from 2005 to 2050 in the baseline case.

The baseline scenario expects primary energy consumption to grow more than five-fold from 2005 to 2050. The shares of nuclear power and renewable energy increase slightly, and among fossil fuels coal becomes increasingly important, which reflects the availability of domestic and other cheap coal resources in the region.

The Indian study also includes climate change stabilisation scenarios developed as part of a general sustainable development model for the whole economy. This model emphasises changes in consumption patterns, urban planning, recycling and greater use of renewable energy as ways of meeting goals for both climate change and general development. Altogether energy efficiency, reduced consumption, recycling and material substitution contribute about 35% of the total CO_2-equivalent emission reduction in this scenario. The resulting synergies produce a significant increase in the penetration of renewable energy in 2050 (Table 1). In the Sustainable Development and Climate Change Stabilisation scenario, the contributions from hydropower, wind and biomass by 2050 are significantly higher than in the baseline case, ensuring that India stays abreast of global emissions targets to

Figure 4
Baseline primary energy consumption for India, 2005-2050



stabilise CO_2 at 450 ppm. The Indian CO_2-equivalent emissions are, as part of this global 450 ppm scenario, increasing by about 50% from 2000 to 2050.

The Sustainable Development and Climate Change Stabilisation scenario predicts a 22% fall in total primary energy consumption by 2050 compared with the baseline scenario. In addition to the assumed increases in hydropower, wind and biomass, this scenario also assumes that almost 300 Mtoe of solar energy with a high share of PV will be added in 2050 relative to the baseline case. CCS contributes about 10% of the greenhouse gas emission reduction in this scenario. Note, however, that even in the Sustainable Development and Climate Change Stabilisation scenario fossil fuels, in particular coal, are expected to cover more than 50% of primary energy consumption in 2050.

Similarities between the three studies

The three scenario-based studies assessed above all conclude that fossil fuels will continue to contribute about 80% of the world's primary energy throughout this century if high energy security and climate change are not high policy priorities.

However, the scenarios to some extent reflect the idea that oil resources could become scarcer and more expensive. This implies that within 30-40 years from now, coal and gas consumption will be increasing faster than oil.

Some of the studies assume that new oil resources could become available later in the century, as a result of new exploitation technologies, though this must be considered rather uncertain. However, new discoveries are expected to give OECD members a larger share of the world's oil and gas supply, increasing the energy security of these countries and so reinforcing their continued large-scale use of oil and gas. The studies suggest that without special policies, renewable energy will not see rapid take-up. The assumption is that renewables will remain more expensive than fossil fuels, even when the latter carry the extra cost of CCS.
Climate change stabilisation scenarios aimed at keeping global temperature rise low imply faster penetration of renewable energy, but even here fossil fuels will still provide about 50% of global primary energy in 2100. Since this will require fossil fuel power plants to use CCS, a critical issue is how well CCS will work in practice.

The Indian case study shows that a large increase in the penetration of renewable energy is to be expected when sustainable development is aligned with climate change goals. Such

Table 1
Contributions of hydropower, wind and biomass in 2050 in baseline and sustainable development scenarios for India

	Baseline scenario	Sustainable Development and Climate Change Stabilisation scenario
Hydropower (GW)	150	250
Wind (GW)	65	200
Biomass (Mtoe/yr)	155	200

The Indian study included another scenario variant which assessed climate change stabilisation more narrowly, without assuming sustainable development in other areas. Here, renewable energy is less prominent than in the Sustainable Development and Climate Change Stabilisation scenario, and wind energy accounts for a higher share relative to commercial biomass and solar power. This reflects carbon prices that are higher than in the sustainable development scenario, making wind energy more attractive, and the fact that a less sustainable development path reduces the availability of biomass with more land for urban areas and less emphasis on agricultural development and forests.

an integration of policy objectives also cuts the cost of India's eventual participation in a global 450 ppm stabilisation scenario, from \$200/t CO_2 in a conventional climate change scenario to \$120/t CO_2 in a scenario addressing both sustainable development and climate change.

The extent to which renewable energy will replace fossil fuels depends on assumptions about costs and availability. The models used in such long-term studies are by nature very aggregate and general. They include little detail on regional potential for specific renewable energy technologies, which in the case of wind power and bioenergy, for example, can be very site-specific. This may mean that some of the potential and costs assumed in the models are high when compared with more detailed studies at national or sub-national level that can assume the utilisation of very attractive local renewable energy sites or resources. Furthermore, the cost data used in the global studies only reflect the costs that can be directly associated with climate change mitigation, energy systems and macro-economic costs. There can be other direct or indirect impacts of introducing renewable energy options such as, for example, local environmental impacts, job creation, innovation spillovers etc. that in reality are key drivers for renewable energy penetration. As a result, it may be no surprise that many global modelling studies end up predicting relatively small proportions of renewable energy compared with what is the outcome of more detailed technology assessments.

Conclusions

Scenario-based studies of global energy and climate change mitigation, and a study specific to India, show that introducing large volumes of renewable energy will require additional efforts beyond what is assumed in the studies about climate change stabilisation that are reviewed in this chapter. According to these studies, the extent to which fossil fuels are replaced by renewables depends on a number of critical but also rather uncertain assumptions, including the discovery of new oil and gas resources in the latter part of the century; the costs and reliability of CCS, and its suitability for bioenergy as well as fossil fuel power plants; and the potential and costs of new commercial bioenergy sources. Furthermore, the penetration of renewable energy will also depend on a set of broader policy priorities relating to the local environment, employment, innovation spillovers and business development.

The increasing interest in green energy as part of national political agendas relating to the "green economy" is a factor which may rapidly change the assumptions underlying the models. Countries like the USA, China and South Korea, for instance, are all aggressively promoting investments in renewable energy and energy efficiency. This political market stimulus is a factor which many of the global models have not yet captured.

4
Energy scenarios for Denmark and Europe

Kenneth Karlsson, Olexandr Balyk and Poul Erik Morthorst, Risø DTU; Maryse Labriet, ENERIS, Spain

Introduction

The challenge of avoiding dangerous climate change will demand massive greenhouse gas (GHG) reductions in the EU and other OECD countries. According to the IPCC (Metz et al. 2007), limiting the global mean temperature rise to 2°C (450 ppm CO_2eq) will demand a global reduction in GHG emissions of 50-85% before 2050. For the world to achieve this and still leave room for economic development, the OECD countries must reduce their GHG emissions by 80-95% before 2050.

A reduction of 80-95% in GHG emissions would require many countries' energy systems to become net CO_2-free in the second part of the century. This means that energy conversion should either not rely on fossil fuels at all, or should include carbon capture and storage (CCS); "negative emissions", created for example by equipping biomass-fired power plants with CCS, would also be needed to compensate for emissions that cannot be mitigated, such as some of those from agriculture (Labriet et al. 2010; Loulou et al. 2009).

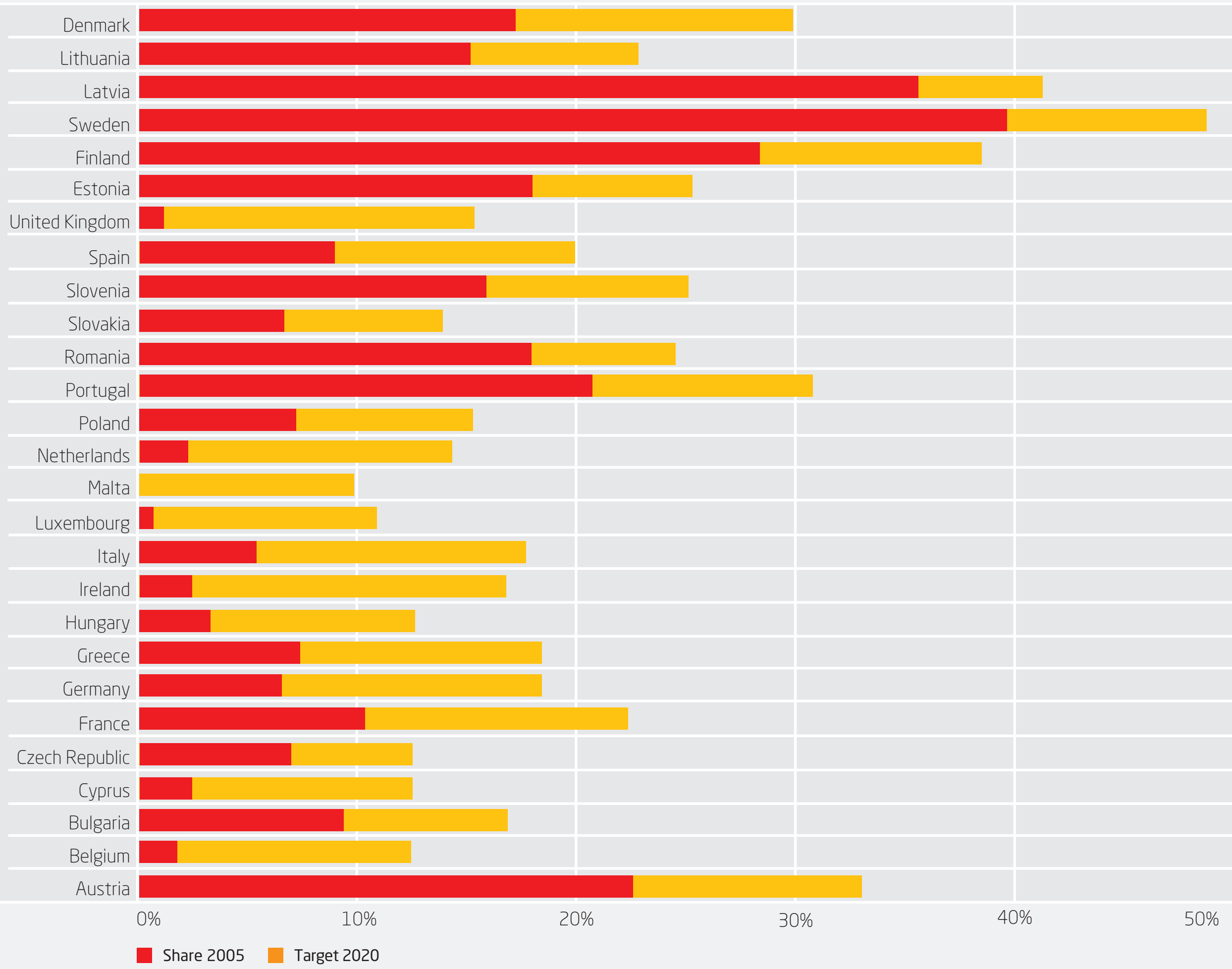
With this challenge in mind, researchers have used various modelling systems to create scenarios for future energy consumption and conversion in Europe as a whole, the Nordic countries and Germany.

The important questions are whether Europe and Denmark can reduce GHG emissions to the required extent, and how much this will cost.

GHG reductions in the EU

The EU member countries face a double challenge. First, if current energy and transport policies remain in place, emissions of CO_2 from the EU area will increase by approximately 5% by 2030 compared to 1990 level (Capros et al. 2008). This is worrying at a time when the climate seems to

Figure 5
Proportion of final energy demand covered by renewable energy sources. Renewable energy targets as agreed by the EU member states



be changing even faster than was expected a few years ago, and when CO_2 emissions from the industrialised countries should be on the decrease. Second, the EU is becoming ever more vulnerable with regard to the security of its energy supplies. A continuation of existing trends implies that the EU's proportion of imported energy, presently 50%, will rise to approximately 65% in 2030.

In facing these challenges the EU has in recent years adopted a fairly ambitious energy and climate change policy. Expressed as "20-20-20 by 2020", the targets imply that by 2020:

- greenhouse gas emissions will fall by 20% compared to 1990;
- renewables will cover 20% of final energy demand; and
- energy consumption will fall by 20% compared to a baseline development.

As an example of how these targets will affect the EU member states, Figure 5 shows their respective contributions to the renewable energy target.

Figure 5 makes it clear that all the member states' individual renewable energy targets are quite ambitious. Taken together with the requirements of climate change policies, these targets will require drastic changes in the energy systems of all countries in both the short and the long term.

In the following discussion, focus is on long-term scenarios for the EU countries, up to the end of this century. To the EU27 countries we have also added three associate member countries: Norway, Switzerland and Iceland.

Modelling for the EU27+3

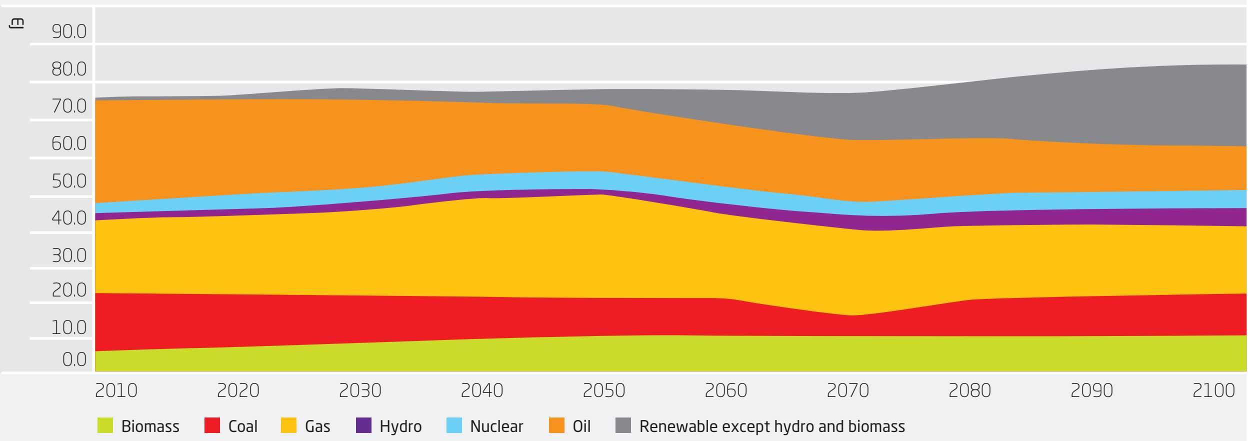
The scenarios for the EU27 countries plus Norway, Switzerland and Iceland (EU27+3) were examined using the global energy system model TIAM-World. The EU27+3 countries form one of 16 regions in the model (Loulou and Labriet 2008; Loulou 2008).

TIAM-World is a detailed, technology-rich global TIMES[1] model. TIAM-World is a partial equilibrium model, where equilibrium in the energy system is found via linear programming. It is able to model and optimise the entire global energy system from the bottom up, from primary resource extraction to end-use, including upstream energy use and emissions from the mining of fuels.

TIAM-World has many capabilities which normally fall outside the scope of energy system models, such as mining and trading in fuels, and modelling fuel prices. It also includes climate equations to calculate GHG concentrations in the atmosphere and the oceans, the consequential changes in radiative forcing, and hence changes in global mean temperature (Loulou and Labriet 2008; Loulou 2008).

Many modelling groups have tried to produce GHG reduction scenarios aiming at a maximum 2°C increase in global mean temperature (stabilising around 450 ppm CO_2eq), but not many have been able to come up with feasible solutions (EMF22 2009), especially not if the reduction target for the developing countries is delayed (so-called "late entry"). This shows the difficulty of the problem: The models simply do not include enough mitigation options, such as energy sub-

Figure 6
Total primary energy consumption (including mining) in the EU27+3 countries in the 550 ppm CO_2eq stabilisation scenario.



[1] *TIMES refers to both a model generator and a family of models. Further information is available at http://www.etsap.org/tools/TIMES.htm.*

stitution, demand adjustments, and biological, geological or oceanic sinks.

This also applies to the version of TIAM-World used in the analyses below; developed primarily for the energy sector, it cannot reach stabilisation at 450 ppm CO_2eq without adding mitigation options at end-use level and from other sectors, such as non-energy-related emissions from agriculture and the manufacturing industry. This limitation made it necessary to relax the requirement for stabilisation, setting the target at 550 ppm CO_2eq instead.[2]

Accordingly, the results presented here show how the EU27+3 countries can play their parts in a global GHG reduction scenario stabilising at around 550 ppm CO_2eq by the end of the period studied (2100). This assumes perfect cooperation between all countries, including the developing countries, so that marginal abatement costs and CO_2 prices are the same across the world.

This does not take into account the need for OECD countries to make larger reductions than developing countries before 2050, but it represents an ideal that is useful in exploring the most cost-efficient global strategies.

Such a scenario also excludes the allocation of emission targets to individual countries, as is currently under discussion in international negotiations. Such an allocation, with an associated market in emission allowances, can of course also be explored with a model like TIAM-World (Labriet et al. 2010).

The EU27+3 nations can manage stabilisation at 550 ppm CO_2eq if by 2050 they can reduce their GHG emissions by slightly more than 40%. Figure 6 shows some results for Europe over the time horizon 2010-2100. Even though focus is on the period up to 2050, the model is run until 2100 to make sure that GHG concentrations do not start to rise again after this time. Overshooting the target is allowed before 2090.

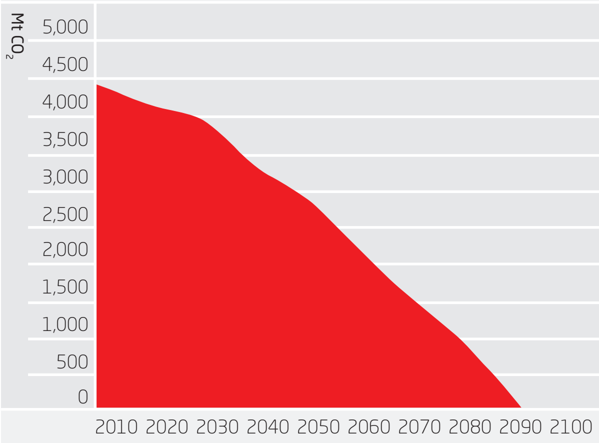
The model shows that stabilisation at 550 ppm CO_2eq would make the global and EU27+3 energy system cost 3-4% more than a reference case with no binding target (based on comparison of net present values of total system cost discounted at 5%). This estimate does not, however, take into account any allocation of and trading in emission allowances between countries, so the extra cost could vary a lot from region to region and from country to country, depending on how the burden is shared.

The global GHG reduction target creates a global price for GHGs in the model. This GHG price will influence the choice of technologies and fuels being at the level of secondary transformation (power plants and heating, hydrogen etc.) or final end-uses (transport, motors, cooling, cooking, heating etc.), as well as the general level of demand for energy. The result is that during the period studied, the EU27+3 countries maintains their primary energy consumption at around 70,000 PJ/yr by obtaining more energy from GHG-neutral sources, especially wind and solar power.

Running the model without a restriction on GHGs leads to a 30% increase in primary energy consumption by 2050 compared to 2010. In this case, the main trends in primary energy are decreases in the share of oil and coal, and increases in the proportion of gas, nuclear power and renewables.

Even a relatively modest target such as 550 ppm CO_2eq means a drastic long-term reduction in GHG emissions from the EU27+3 countries, with energy-related net CO_2 emissions having to fall to zero before 2090. This can be done by introducing more renewables and by adding CCS technology to power plants and industrial processes wherever possible, including those firing biomass (Figure 7).

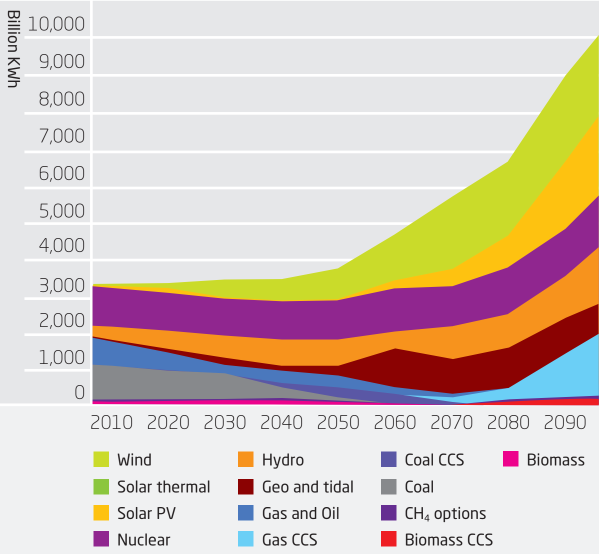
Figure 7
Total energy-related CO_2 emissions for the EU27+3 countries in the 550 ppm CO_2eq scenario



Most of the GHG reductions would be achieved in the power sector by phasing out conventional coal and more than half of traditional gas firing before 2050, while alternative technologies such as wind, geothermal and tidal power become competitive. In 2050, the model shows that 32% of electricity comes from nuclear power plants and 26% from wind power. Nuclear production does not grow throughout the

[2] The restriction to the model is actually implemented as an allowed increase in radiative forcing, to 3.5 W/m². According to the IPCC (Metz et al. 2007), this corresponds to stabilisation at 535 ppm CO_2eq.

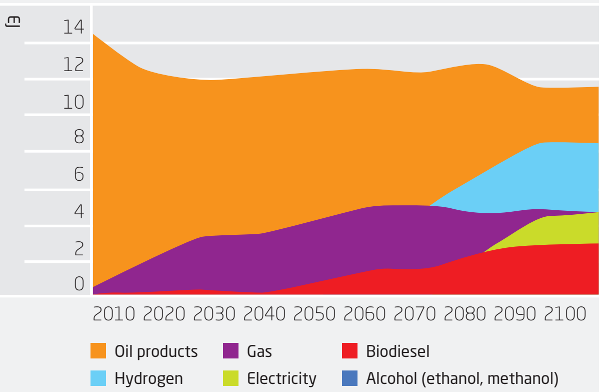
Figure 8
Electricity production by fuel for the EU27+3 countries in the 550 ppm CO_2eq scenario



period modelled as in this scenario its production capacity was fixed to reflect uncertainty regarding its acceptance in future. On the other hand, any phase-out of nuclear power in Europe could, of course, increase the share of other low-carbon power plants, and sensitivity analyses of this may deserve attention in future work. Gas and coal-fired power with CCS technology appears around 2030, but even by 2050 accounts for just 4-5% of power production (Figure 8).

GHG mitigation in transport is more difficult and expensive, so changes in this sector are less marked in the period leading up to 2050. After 2050 there is a switch first to biodiesel, and later to electric vehicles and hydrogen (Figure 9). Note that the TIAM-World model has no option for modal shifts (i.e. replacing one form of transport by another) in the transport sector.

Figure 9
Fuels for road transport in the EU27+3 countries in the 550 ppm CO_2eq scenario



The conclusion of this brief analysis is that the EU27+3 countries can cut their GHG emissions by at least 40% before 2050 without significant extra costs relative to their GDP – and with huge potential remaining for further reductions, since the model shows that up until 2050 the transport sector is still running on fossil fuels (except for a small amount of biodiesel). Renewable energy for power, heat and transport purposes is not exploited to anything like its full potential in this scenario, so a lot more can be done, although costs might then increase. Analyses assuming stricter targets for Europe up to 2050 show different conclusions, however (Labriet et al. 2010).

GHG reductions in Denmark

Compared to Europe as a whole, Denmark is a special case: The country is notable for its history of development towards a flexible energy system incorporating renewable energy sources, and its exchange of electricity with neighbouring countries. After an introduction to the existing Danish energy system, therefore, the following sections take this trend to its logical conclusion by describing a scenario involving a total phase-out of fossil fuels in Denmark.

Since the beginning of the 1990s, Denmark has treated climate change as one of the important driving factors for national energy policy. The results have included strong measures to improve energy efficiency and conserve energy, and the development and implementation of carbon-efficient technologies such as cogeneration and wind power. Since Denmark is a member of the EU, this development is driven by the EU as well as national policies.

The Danish energy system has three main characteristics:

- Denmark has a diverse and distributed energy generation system based around three national grids for power, district heating and natural gas. The combination of these grids implies that Denmark has a highly efficient energy supply system with a high proportion of combined heat and power.

- Renewable energy, especially wind power, plays a large and increasingly important role in the Danish energy system. At present 20% of Danish power demand is met by wind and Denmark is the global front-runner in the development of offshore wind farms. It is envisaged that by 2025 wind power will provide more than half of the country's power needs.

- Denmark's geographic position between the European continent and the Nordic countries allows the country to act as a buffer between the Nordic and the European energy systems. As a member of the Nordic power exchange, Nord Pool, Denmark trades power extensively with the Nordic countries and Germany, and also handles considerable volumes of transit power between the continent and the other Nordic countries. The Danish natural gas grid connects Sweden with Germany.

Denmark is the only country in the EU which is a net exporter of energy. In 2008, production from Danish oil and gas fields in the North Sea exceeded the country's gross energy consumption by approximately 75%. Furthermore, for more than 20 years Denmark has succeeded in keeping its gross energy consumption almost constant, despite the fact that GDP has increased by more than 80% over the same period.

From the above it is clear that in terms of energy Denmark is far better off than most EU countries. Nevertheless, Denmark also faces a number of challenges; some of these are general to the EU, while others are specific to Denmark:

- Oil and gas production peaked in 2005 and will gradually decrease to a level below domestic consumption, thus increasing the vulnerability of the Danish energy supply. To mitigate the country's increasing dependence on imported fossil fuels, the government has set up a Climate Change Commission whose task is to come up with policy measures that will phase out fossil fuels within the next 50 years. These measures will also be vital to the national climate change policy in reducing Danish emissions of GHGs.

- Combined heat and power, together with an extensive district heating system, is the cornerstone of Denmark's highly efficient energy system. However, the widespread use of small-scale CHP plants has taken the heating market to its limit, so the potential for expansion is modest.

- With 20% of all its electricity supplied by wind turbines, Denmark has the highest proportion of wind power in the world. Accommodating more wind power will require innovative solutions.

- Transport is the only sector in Denmark to be increasing its use of energy. Replacing fossil transport fuels with renewable energy sources is a major challenge for the future.

New policies are therefore required which – relying increasingly on renewable sources – will change the Danish (and European) energy systems radically in the coming decades. The following scenarios show the extent to which the Danish energy system could actually change in future.

Modelling for Denmark

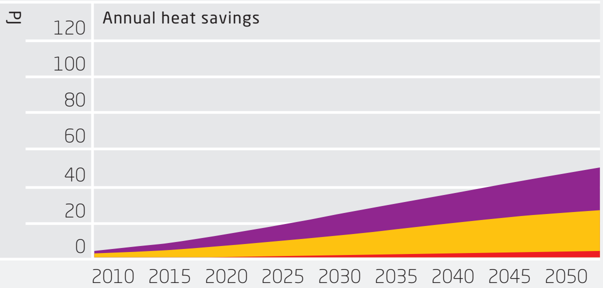
The setup used for the Danish projections consists of a macro-economic model to forecast energy demand, an energy system optimisation model describing the production of electricity, heat and transport fuels, and a spreadsheet model of the complete national energy balance, including the transport sector.

Energy demand forecasts for the Danish economy up to 2050 are based on the macro-economic model ADAM[3] used by the Danish Ministry of Finance. This projection of economic activity in different sectors is then transformed into a demand for energy by the econometric sector model EMMA[4]. Possible energy savings are evaluated using cost curves for each sector, and implemented as efficiency trends in EMMA.

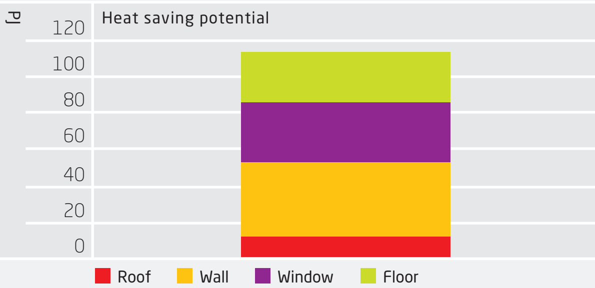
The optimum split of investments in heat savings and in the supply of electricity and heat are analysed in the energy system optimisation model Balmorel[5]. The model version used here is a special version developed by the Centre for En-

Figure 10

Implemented heat savings up to 2050 for the 24 heating areas in the Balmorel model



Total heat saving potential for the 24 heating areas in the Balmorel model



[3] *ADAM is maintained by Statistics Denmark. See http://www.dst.dk/homeUK/guide/ADAM.* [4] *EMMA is maintained by the Danish Energy Agency. Detailed model description is available at http://www.ens.dk/en-US/Info/FactsAndFigures/scenarios/model/EMMA.* [5] *http://www.balmorel.com*

ergy, Environment and Health[6] (CEEH). Compared to the original, the CEEH version includes more sectors, and also external health-related costs caused by air pollution from energy conversion processes. Heat demand and production are divided into 22 heating areas linked by the district heating grid, plus two areas (one in western and one in eastern Denmark) to which the grid does not yet extend.

This modelling framework does not cover the global energy markets, so fuel and CO_2 prices are therefore exogenous to the model. The set of prices used is based on the WEO 2009 "450 ppm" scenario (IEA 2009) up to 2030, after which time fossil fuel prices are projected to remain constant because of low demand. The CO_2 price, on the other hand, has risen to €75/t CO_2 by 2030, and this trend is projected to continue, resulting in a price of €155/t CO_2 by 2050.

Biomass prices are assumed to sit between those of coal and natural gas until 2030. After that, due to high demand for biomass in a world with ambitious reduction targets, biomass prices are assumed to rise so that they match natural gas by 2050.

On the demand side, the efficiency of electrical appliances improves by 2.1% per year until 2050, while Balmorel is used to predict heat savings in each of the heating areas (Figure 10). To do this, a module developed for Balmorel by Erika Zvingilaite and Olexandr Balyk from Risø DTU balances the investment needed to save heat against that needed to build new heat supply capacity. Figure 10 shows that in this particular model run, by 2050 more than 50% of the potential heat savings in the existing building stock have been realised.

Energy for industrial processes is switched away from fossil fuels by increasing the proportion of electricity used and by using more biomass. Transport, which is the most difficult and expensive sector to decarbonise, is switched towards electrical vehicles and fuels such as hydrogen, methanol and biofuels. These transport fuels will be important to the flexibility of the future energy system because their manufacture can stabilise the power grid by absorbing excess wind power when necessary. To force the model to create an energy system without fossil fuels, the model is simply prevented from investing in fossil-fuel heat and power plants after 2025. The transport sector is not expected to be fossil-free before 2050.

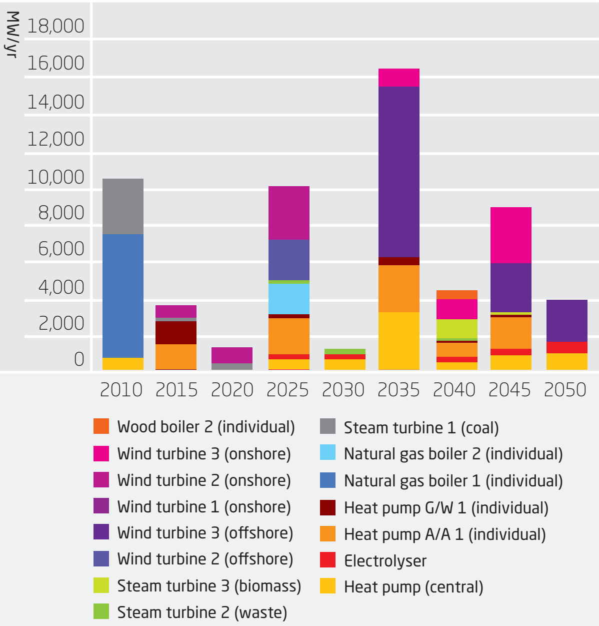
The energy supply system modelled in Balmorel produces electricity, heating (both individual buildings and district heating) and the transport fuels mentioned above. To capture the power market of which Denmark is part, the surrounding countries, i.e. Finland, Sweden, Norway and Germany, are modelled as well. The model runs with endogenous investment by minimising total system costs in the Nordic countries and Germany. The model will then find the optimum economic solution for the whole region.

Figure 11 shows the investment by the model in Denmark in five-year steps, so each column covers investments in the previous five years.

To start with, the model still builds gas and coal-fired power plants, but from 2015 onwards investment is mainly in heat pumps and wind power. Investments in electrolysers for hydrogen and methanol start in 2025. In 2035, there are huge investments in offshore wind power because of the extra power demand from heat pumps and the transport sector, and because of the retirement of older plants.

The model divides heat production into district heating grid areas and individually heated areas. Coal is used in central CHP plants which are also co-fired with waste. Natural gas is used for primary and local CHP generation as well as in individual boilers. As the CHP plants are phased out, they are replaced by large heat pumps and waste-fired CHP plants. Individual heating is taken over by small heat pumps and some wood-burning boilers and stoves.

Figure 11
Investment in different technologies; each column shows the amount invested during the previous five-year period



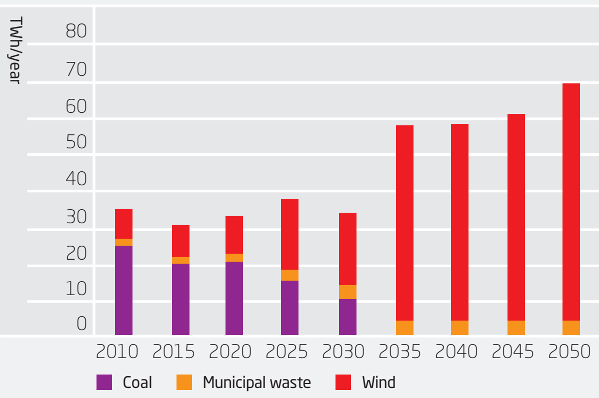
[6] *http://www.ceeh.dk*

Power in the future Danish energy system will come mainly from wind turbines – onshore to begin with, and later offshore, once the price of CO_2 has risen to the point where this becomes economical.

In the scenario presented here, in which fossil fuels are still abundant in the power sector by 2025, the model invests mainly in wind power, but also in waste incineration plants and some biomass-fired gas turbines. With the fuel and CO_2 prices assumed here, the wind power solution is only marginally more expensive than coal power with CCS. As a result, the cost of eliminating fossil fuels is less than 1% more than the base scenario with no restrictions on energy source. However, this estimate does not include the costs of changing transport technologies, which could easily change the picture.

Figure 12 shows electricity generation according to fuel. Even though existing gas and biomass-fired CHP plants remain available until 2020, the model chooses not to use them because they cannot compete with coal and wind in the power market under the assumed price regime. After 2030, when the last coal-fired power plant is decommissioned, the model invests in some gas turbines running on gasified biomass to provide backup capacity when there is no wind. These gas turbines operate for so few hours a year, however, that they cannot be seen on the graph.

Figure 12
Electricity production by fuel



The massive amount of wind power in the Danish system is balanced by managing demand, production and transmission. By 2050, power demand is assumed to be very flexible, allowing demand to move from peak periods with no wind to periods when there is plenty of wind. Production is balanced through heat pumps and heat storage, and by producing hydrogen or methanol for the transport sector. Finally, Denmark's extensive transmission grid can move power to and from neighbouring countries. Without all this flexibility it would not be possible to integrate such a large share of wind power.

Conclusions

The EU scenario shows that if the world is to stabilise the atmospheric concentration of GHGs at 550 ppm CO_2eq or less, the European countries will have to reduce their GHG emissions by at least 40% by 2050.

However, this is only possible if we include all global mitigation options, without taking into account the fact that the need for development means that some parts of the world, for example Africa, may need to delay their entry to the GHG reduction process. Once we take into account late entry for some regions, the EU countries will have to cut their emissions by much more than 40% even to meet the 550 ppm CO_2eq target.

For the 450 ppm CO_2eq scenario, the EU would probably have to reduce GHG emissions by 80-95% by 2050. The extreme difficulty of meeting the 450 ppm CO_2eq target is underlined by the fact that only a few modelling groups have been able to produce global energy model scenarios keeping within this target.

As stated above, the version of the TIAM-World model used in the present analyses was primarily developed for the energy sector, and cannot solve the need for stabilisation at 450 ppm CO_2eq without adding more mitigation options. A lot more work therefore needs to be done to identify new mitigation options which can be added to the models if they are to help guide us towards the 450 ppm CO_2eq target.

On the other hand, the Danish case shows that some countries will be able to phase out fossil fuels rapidly enough to stabilise GHG levels – if only this could be done on a global scale – at 450 ppm CO_2eq.

Especially because of its wind resources, Denmark can phase out fossil fuels from electricity and heat production before 2040. Removing fossil fuels from the transport sector will probably take a further 10 years. The increased costs of such a transformation in the electricity and heat sector will range from zero to just a few per cent, but the extra cost in the transport sector is very uncertain.

Exogenous assumptions about the prices of fuels, CO_2 and technology have big impacts on the energy system. Despite this, sensitivity studies demonstrate the robustness of one of the most important conclusions: That a "fossil-free" Denmark will incur low or even no extra socio-economic costs.

5
Solar energy

P. Sommer-Larsen and Frederik C. Krebs, Risø DTU, Denmark; Diego Martínez Plaza, Plataforma Solar de Almería-CIEMAT, Spain

Solar energy is the most abundant energy resource on earth. In a sustainable future with an ever-increasing demand for energy, we will need to use this resource better.

Solar energy technologies either convert sunlight directly into heat and electrical energy or use it to power chemical conversions which create "solar fuels" or synthetic compounds.

Solar heating technologies have developed steadily for many years and solar heating and cooling is one of the world's commonest renewable energy technologies. This chapter, however, focuses on technologies for electricity production and touches more briefly on the prospects for solar fuels. The section on Danish perspectives also discusses solar thermal heating in district heating plants.

In recent decades, two technologies for converting solar energy into electrical energy have dominated: photovoltaics (PV) and concentrating solar power (CSP). Today's silicon and thin-film PV technologies are advancing steadily, with new materials and technologies constantly being developed, and there are clear roadmaps for lowering production costs. In the discussion below we assess the maturation potential of currently emerging PV technologies within the next 40 years.

Concentrating solar power is already a proven technology, and below we evaluate its potential to become a substantial part of the energy mix by 2050. Solar fuels cover a range of technologies.

The chapter is to a great extent based on two recent roadmaps from the International Energy Agency (IEA). Many reports, predictions, scenarios and roadmaps for solar energy deployment exist. The IEA predictions for the penetration of solar energy in the future energy system are low relative to many of the other studies. The IEA roadmaps, however, cover most aspects of the future deployment of the technologies and reference older work.

Photovoltaics

In its recent technology roadmap [1], the IEA concludes that solar PV power has significant potential for long-term growth in nearly every region of the world. The IEA estimates that by 2050 PV will provide around 11% of global electricity. The installed PV capacity increased by 50% in 2009 to 22 GWp. The roadmap prediction assumes a decreasing growth rate in the next decades reaching 200 GWp of installed capacity by 2020, 900 GWp by 2030 and 3,000 GWp by 2050.

According to the IEA, PV energy prices will match retail electricity prices ("grid parity") before 2020 in most regions of the world. The IEA roadmap, like almost all other studies, says that financial incentives are needed to support the deployment of PV, allowing a combination of increasing production and market competition to drive down the industry's costs. Once PV reaches grid parity, the IEA roadmap foresees changes in policy frameworks and the creation of a self-sustaining market while guaranteeing PV owners the right to sell power to the grid.

The cost of PV electricity varies according to the amount of sunshine, financial terms, installation type and PV technology. Despite this variation, the IEA has set cost reduction goals (Table 2) based on the Strategic Research Agenda and

Table 2
IEA cost reduction goals for PV [1]

Cost targets for the residential sector		2008	2020	2030	2050
Typical turnkey system price (2008 $/kW_p$)		6,000	2,700	1,800	1,200
Typical electricity generation costs (2008 $/kWh)[1]	2,000 kWh/kW$_p$[2]	0.36	0.16	0.10	0.07
	1,500 kWh/kW$_p$[2]	0.48	0.21	0.14	0.09
	1,000 kWh/kW$_p$[2]	0.72	0.32	0.21	0.14
Cost targets for the commercial sector		**2008**	**2020**	**2030**	**2050**
Typical turnkey system price (2008 $/kW$_p$)		5,000	2,250	1,500	1,000
Typical electricity generation costs (2008 $/kWh)[1]	2,000 kWh/kW$_p$[2]	0.30	0.13	0.09	0.06
	1,500 kWh/kW$_p$[2]	0.40	0.18	0.12	0.08
	1,000 kWh/kW$_p$[2]	0.60	0.26	0.17	0.11
Cost targets for the utility sector		**2008**	**2020**	**2030**	**2050**
Typical turnkey system price (2008 $/kW$_p$)		4,000	1,800	1,200	800
Typical electricity generation costs (2008 $/kWh)[1]	2,000 kWh/kW$_p$[2]	0.24	0.11	0.07	0.05
	1,500 kWh/kW$_p$[2]	0.32	0.14	0.09	0.06
	1,000 kWh/kW$_p$[2]	0.48	0.21	0.14	0.09

[1] Assumptions: interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050); operations and maintenance (O&M) costs 1%.
[2] Capacity factor; the amount of electricity generated by a PV system per W$_p$ per year; a typical range is 1,000–2,000 kWh/kW$_p$.

the Implementation Plan of the European PV Technology Platform (2007, 2009), the Solar America Initiative (DOE 2007), the Japanese PV roadmap towards 2030/PV2030+ (NEDO 2004, 2009) and the IEA Energy Technology Perspectives 2008. All cost targets are based on solar cell modules rated power in Watt-peak (Wp).[7]

A variety of PV technologies exist, and few other renewable energy technologies boast such a portfolio of available technical options at different levels of maturity. This is one of the premises behind the expectation that the cost of PV will continue to fall for a long time.

Crystalline silicon solar cells and thin-film solar cells are well-established, yet roadmaps for these technologies still identify clear potential for substantially lower production costs in the next decade.

In addition, emerging technologies promise improved efficiencies, high-volume production and even ultra-low costs. These technologies include cheap organic solar cells, high-efficiency multi-junction concentrator cells, quantum dot structures and other novel semiconductor technologies.

The cost of PV production falls by nearly 20% with every doubling of production capacity, and the hope is that the emerging technologies will jump onto this curve (fig. 13) as they mature. In the meantime, the wide variety of applications for PV allows the various technologies to develop their own markets: from niche products like consumer electronics, through standalone PV systems, to Building Integrated PV (BIPV) and bulk electricity production.

For a number of years, the demand for PV exceeded production capacity, and suppliers defined the market and prices. In 2009, however, the global financial crisis, the collapse of the Spanish market and especially the build-up of production capacity led to a dramatic fall in PV module prices. According to Pike Research [2], the market is now demand-led and competes on price. In the long term, the competition between the established and emerging PV technologies will favour the technologies with the lowest system life span costs calculated over a given time span, i.e. a 25-year period.

PV technologies are demanding of materials, and the availability of materials is an issue if PV is to be widely used. Silver (Ag), Indium (In), Cadmium (Cd) and Tellurium (Te) are some of the elements commonly used in solar cells that are relatively rare: Known reserves will be exhausted in 10-20 years at the current extraction rate. As a result, some PV technologies will simply be limited by shortages of materials.

As an example, the IEA foresees a total installed PV capacity of 3,000 GWp by 2050. If these solar cells are all of the CdTe type (see below) with a 1 µm CdTe layer and 15% efficiency, this will require 100,000 t of CdTe – vastly more than the world's known Te reserve of 21,000 t [3].

Although recycling and technical advances will reduce such limitations, shortages of materials for both solar cells and balance-of-system (BOS) components[8] will continue to threaten the PV market as it grows. One conclusion is that we will need the full range of PV technologies to create an elastic market which can respond to changes in demand.

In conclusion, in the short term, current PV technologies are likely to benefit from economies of scale to the point where they reach grid parity and a total installed capacity of at least 200 GWp by 2020. A broad portfolio of PV technologies will support a continued capacity build-up over the next 40 years, at least to the level of the IEA estimate of 11% of global electricity production from PV by 2050. Current PV technologies will co-exist with emerging and novel technologies in the market.

PV technologies

Crystalline silicon (c-Si) solar cell modules currently make up 85-90% of the global market. Single crystalline (sc-Si) modules show power conversion efficiencies of up to 20% and are more expensive than multi-crystalline (mc-Si)[9] modules, which have efficiencies of up to 15%. The two classes share the market equally.

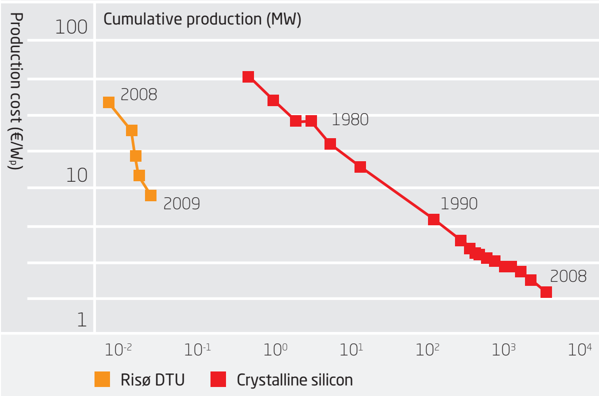
Thin-film solar cells currently account for 10-15% of global PV module sales. Amorphous (a-Si) and micromorph silicon (a-Si/µc-Si) modules have relatively low efficiencies (8%), whereas cadmium telluride (CdTe) and copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS) show module efficiencies of 10-14%. It is noteworthy that thin-film PV companies report the lowest production costs of all PV technologies: approximately 1$/Wp for CdTe and printed CIGS solar cells.

Emerging technologies include advanced thin-film and organic solar cells (OPV). The latter, which are about to enter the market via niche applications, encompass polymer solar cells, small-molecule solar cells and dye-sensitised solar cells. Polymer solar cells already have a low cost per square metre (Figure 14), but because they are relatively inefficient, their cost per Wp is $8-12 today [4]. Their cost is, however, on a steep descent as illustrated in Figure 13. OPV and Si solar cells are the only PV technologies where the photovoltaic material is not limited by the availability of materials. In

[7] *Watt-peak (Wp); the rated module power measured under standard test conditions: 1,000 W/m^2 light intensity, AM 1.5G spectrum, and 25°C.*
[8] *BOS components: inverter, wires, frames etc.* [9] *Also termed poly-crystalline*

addition, polymer solar cells possess the potential for high-speed production, which may allow for much larger production capacities – in GWp – than other PV technologies.

Figure 13
A comparison [5] between cost and the cumulative production capacity (in MWp) for crystalline silicon solar cells [6] and polymer solar cells based on ProcessOne [7] manufactured at Risø DTU



PV concentrator technologies (CPV) use an optical concentrator system to focus solar radiation onto a small high-efficiency cell. CPV technology is currently being tested in pilot applications.

Novel PV concepts aim to achieve ultra-high-efficiency solar cells via advanced materials and photo-physical processes. They are currently the subject of basic research.

Figure 15 shows predicted developments in power conversion efficiency (PCE)[10]. Other important performance and production parameters like lifetime and energy payback time (EPT)[11] also differ among the technologies. The overall IEA expectation is a gradual increase in lifetime for c-Si cells from 25 years today to 40 years by 2050. In the same time span, EPT is likely to decrease from two years to six months. Organic solar cells may reach EPTs as low as a few months, but even the most optimistic guesses put their potential lifetime at only 10 years.

Figure 15
Performance of PV technologies (source [1])

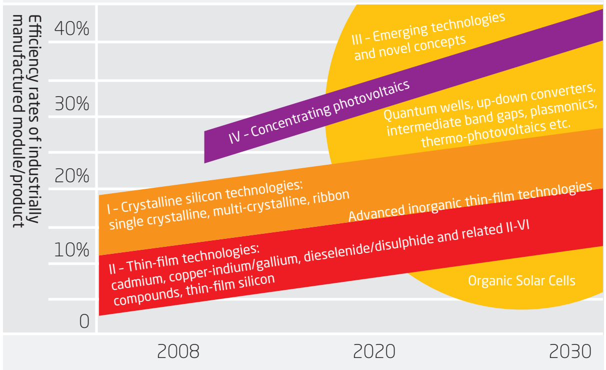
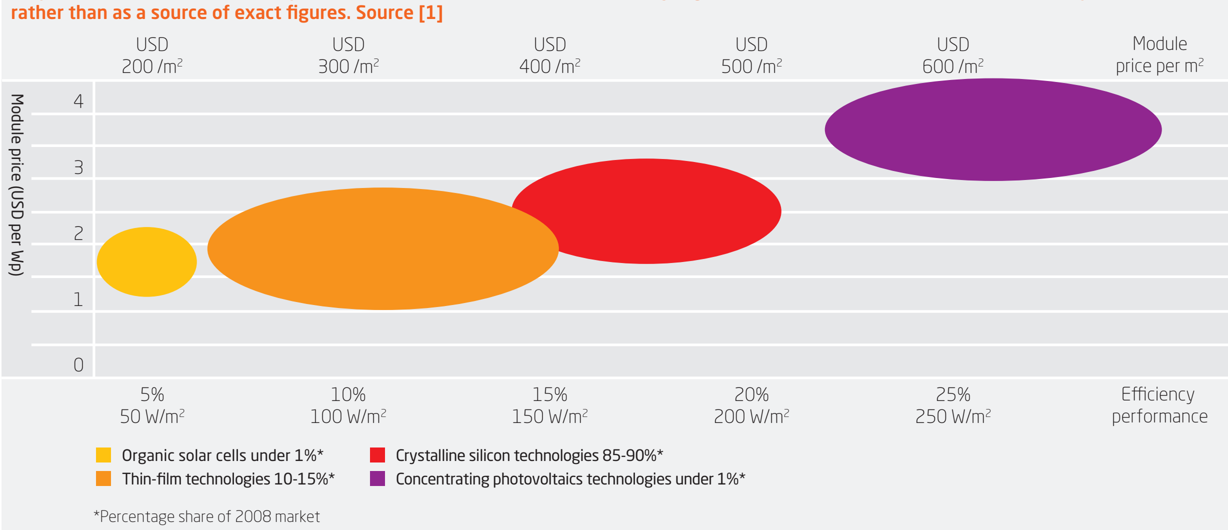


Figure 14 illustrates the ranges of production costs and module prices within which we can expect to find PV technologies.

Concentrating solar power

CSP technology has been used in central power plants for more than 20 years. Mirrors focus solar radiation which

Figure 14
PV production costs and module prices. The uncertainties in the data are very high, so this chart is best used as a tool for comparison rather than as a source of exact figures. Source [1]



[10] *PCE is measured under standard test conditions – see footnote 7*
[11] *Energy payback time, defined as the time needed for the PV system to repay the energy used in manufacturing it.*

heats a receiver to high temperatures. The heat is used to generate electricity by driving a turbine or some other engine. Heat can also be used to generate hydrogen by decomposing water, and to power more complex chemical reactions producing other energy carriers (solar fuels).

The IEA also drew a technology roadmap for CSP [8] indicating that:

- CSP can provide low-carbon, renewable energy resources in countries or regions with high "direct normal irradiance" (DNI) – strong sunshine and clear skies;
- by 2050, with appropriate support, CSP could provide 11.3% of global electricity, with 9.6% coming from solar power and 1.7% from backup fuels (fossil fuels or biomass);
- in the sunniest countries, CSP is expected to become a competitive source of bulk power for peak and intermediate loads by 2020, and for base-load power by 2025-2030.

The possibility of integrated thermal storage is an important feature of CSP plants, and virtually all such plants also have backup capacity in the form of fuel that can be burned to produce power. CSP thus offers firm, flexible generating capacity to utilities and grid operators while also enabling effective management of a greater share of variable energy from other renewable sources, such as PV and wind power.

The IEA envisions North America as the region with the largest production and consumption of CSP electricity, followed by Africa, India and the Middle East.

North Africa is potentially a major exporter (mainly to Europe), since its considerable solar resources largely compensate for the additional cost of long transmission lines. The Desertec Industrial initiative (Dii) aims to realize this vision termed the Desertec Concept [9].

CSP can also produce significant amounts of high-temperature heat for industrial processes. In particular, it can help meet growing demand for water desalination in arid countries.

Given the arid or semi-arid nature of environments that are well-suited for CSP, a key challenge is finding the cooling water needed for CSP plants. Dry or hybrid dry/wet cooling can also be used in areas with limited water resources although at a performance penalty of 7%.

The main obstacle to the expansion of CSP plants is not the availability of areas suitable for power production, but the distance between these areas and many large consumption centres. The roadmap examines technologies that address this challenge through efficient, long-distance electricity transmission.

CSP facilities could start providing competitive solar-only or solar-enhanced gaseous or liquid fuels. Success in these areas affirms the need for larger-scale experiments to support the further development and to establish a basis for evaluating their potential.

CSP technologies

The current CSP systems fall into four main classes depending on the geometrical configuration used to focus the sun's rays, receive the solar radiation and collect the resulting heat: parabolic trough plants, central receiver plants, dish Stirling systems and linear Fresnel systems (Table 3).

Parabolic troughs are the most mature of the CSP technologies and account for the bulk of current commercial plants. Most existing plants, however, have little or no thermal storage and rely on burning fuel to provide backup when the sun is not shining. For example, CSP plants in Spain get 12-15% of their annual electricity production from natural gas. Some newer plants, however, have significant thermal storage – up to 7.5 h@100% capacity.

Central receiver systems (CRSs) use hundreds or thousands of two-axis mobile reflectors (heliostats) to concentrate the sun's rays on a central receiver placed atop a fixed tower. Some commercial tower plants now in operation use direct steam generation in the receiver; others use molten salts to both transfer and store heat. The world's first commercially operating solar tower, PS10, was developed by Abengoa Solar – see Figure 16.

Figure 16: Planta Solar 10 or PS10 solar power tower in Sanlúcar la Mayor near Seville, Spain. 624 heliostats of 120 square metres focus the sun rays on the top of the 115-metre-high tower, where the receiver generates pressurised steam to run a conventional power cycle with 11 MW capacity.

Parabolic dishes concentrate the sun's rays at a focal point propped above the centre of the dish. The entire apparatus tracks the sun, with the dish and receiver moving in tandem. Most dishes have an independent engine/generator (such as a Stirling machine or a micro-turbine) at the focal point. This design eliminates the need for a heat transfer fluid and for cooling water.

Linear Fresnel reflectors (LFRs) approximate the parabolic shape of trough systems by using long rows of flat or slightly curved mirrors to reflect the sun's rays onto a downward-facing linear, fixed receiver. A more recent design known as the compact linear Fresnel reflectors (CLFRs) uses two parallel receivers for each row of mirrors, and thus needs less land than a parabolic trough with the same output.

Deployment of CSP

Today's CSP technology is implemented in the cost range of 15-20 cents€/kWh. In the conventional power market, it competes with mid-load power in the range of 3-4 cents€/kWh.

Sustainable market integration, as predicted in different scenarios, can only be achieved if the cost can be reduced to a competitive level in the next 10-15 years. Competitiveness is not only impacted by the cost of the technology itself but also by a potential rise in the price of fossil energy and by the internalisation of associated social costs such as carbon emissions. Therefore, we assume that in the medium to long term competitiveness is achieved at a level of 5-7 cents€/kWh for dispatchable mid-load power.

Among different scenarios aimed at reducing the actual electricity costs of these technologies, the European Concentrated Solar Thermal Road mapping, ECOSTAR [10] assessed three ways: i) Mass production (e.g. by continuous plant deployment); ii) Scaling of unit size and iii) Implementation of technical innovations.

In the short term (~next 10 years), research challenges should focus on identifying and contributing to implementing the potential technical innovations which would have the highest impact on CSP cost reduction. The research challenges may be divided into three groups:

Increasing modularity:

- Modularity on plant concepts, e.g. multi-tower schemes, more cost-effective dish-Stirling systems.
- Modification of structures, application of new materials and simplification of concentrator system.
- Modularity of spare parts or components, e.g. heliostats and receiver modules.

Increasing efficiency :

- Through plant scheme simplifications by reducing the need for heat exchangers when using different working fluids (as in Direct Steam Generation).
- Further development of the thermodynamic cycle with increased temperatures, or additional superheating for the CRS (Central Receiver System) saturated steam plant may be considered. These measures provide higher efficiencies and solar fractions.
- Provide more cost-efficient solutions of dry cooling to extend widely the potential placements for these plants.

Increasing dispatchability and availability:

- Integration of thermal storage for several full-load hours, together with new storage materials and advanced charging/discharging concepts allow for increased solar electricity production without changing power block size.
- Developing improved strategies for control and operation under cloud transients.
- Improved prediction of dispatch schemes in meteorological predictions and demand and market curves.
- Development of procedures (or methodologies) for lifetime assessment by accelerated aging of materials of principal components such as receiver, driving mechanism.
- Improved operation and maintenance procedures.

Solar fuels

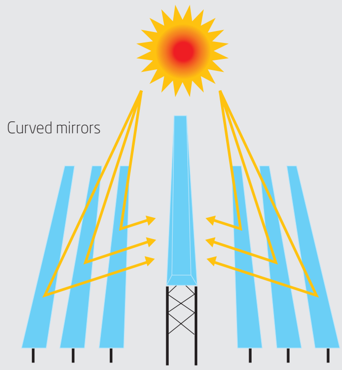
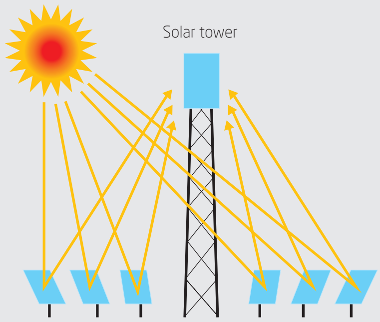
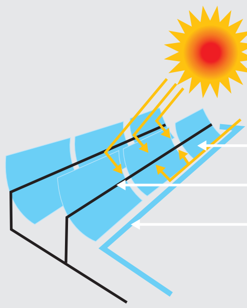
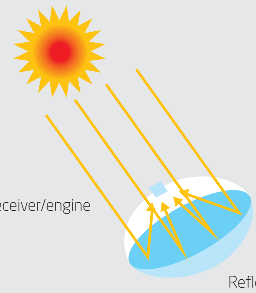
The direct conversion of solar energy into chemical energy is intimately linked to our possibilities for mitigating carbon dioxide, and efficient solutions could potentially solve not only the energy challenge but also the carbon dioxide challenge. Two overall research lines exist:

1) Use of sunlight for the conversion of carbon-free chemicals (i.e. water splitting to molecular hydrogen and oxygen)

2) Use of sunlight for the conversion of carbon-containing chemicals (i.e. photoreduction of carbon dioxide).

While both approaches have been demonstrated at laboratory level, they are both very inefficient, and there are no examples that show promise of facile upscaling routes. In addition, the greatest challenge for both approaches is the associated carbon dioxide emissions. There is currently no available carbon dioxide emission-free source of carbon dioxide, and this implies that available conversion routes for carbon dioxide are limited to reducing carbon dioxide emissions but will never enable a situation where carbon dioxide levels in the atmosphere are reduced; only the rate at which carbon dioxide is emitted will be reduced. There is thus an urgent need for finding carbon dioxide emission-free routes to extracting carbon dioxide directly from the atmosphere

Table 3
CSP types

		Focus	
		Line focus Collectors track the sun along a single axis and focus on a linear receiver. This makes tracking the sun simpler	Point focus Collectors track the sun along two axes and focus at a single point. This allows higher temperatures
Receiver	Fixed Stationary devices which remain independent of the plant's focusing device. This eases the transport of collected heat to the power block	Linear Fresnel reflectors 	Central receiver system (CRS) 
	Mobile Mobile receivers move with the focusing device. In both line-focus and point-focus designs, mobile receivers collect more energy	Parabolic troughs 	Parabolic dishes 

and subsequently efficiently converting it to an energy-rich carrier (i.e. formic acid, formaldehyde, methanol or methane). There is currently ~ 1 teraton of carbon dioxide in excess in the atmosphere [11], and the scale at which we can currently handle carbon dioxide industrially approaches max. 200 megatons. Our infrastructure thus falls desperately short of enabling assimilation of carbon dioxide. This all indicates that new technology is needed that encompasses the chemical scale of at least multi-gigaton if we are to stop the steady increase in carbon dioxide in the atmosphere, or in fact ensure a decrease. The most likely successful approach will employ sunlight and low-cost systems comprising large-area solar catalysts.

CSP may likewise power reactive fuels. A number of conversions have been demonstrated, including water splitting, fossil fuel decarbonisation and the conversion of biomass and organic wastes into gaseous fuels. Larger-scale experiments are needed to support further development. Direct water splitting produces hydrogen at temperatures around 2,500° C. Such high temperatures give rise to many practical problems. An alternative – operational already at 1,200° C – is a thermally driven reduction (de-oxidation) of metal-oxides and subsequent reaction of the metal (Al or Mg) with water to form hydrogen and metaloxide again. Large-scale demonstration is still a premise for evaluating the potential.

A Danish perspective

In Denmark, only PV and solar thermal heating technologies are useful. Half of the daylight takes the form of diffuse scattered radiation, and CSP will not be financially viable because it requires direct solar radiation.

PV is scarcely deployed in Denmark with only 4.7 MW of installed capacity at the end of 2009 [12]. A typical PV capacity factor in Denmark lies in the range 850-1,000 kWh/

kWp, which is only half of the capacity factor in southern Europe. Nevertheless, the Danish Solar Cell Association (www.solcelle.org), which was founded in 2008, has a vision for 5% of the electricity supply in Denmark to be powered by PV by 2020.

Net metering is the only public incentive in Denmark, and it allows residential PV owners to feed electricity back into the grid from systems no larger than 6 kWp. Rooftop-mounted PV and BIPV installations are the basis for PV deployment in Denmark. The installed capacity is divided among residential, industrial and public building installations. In their Strategic Research Agenda for Photovoltaic Solar Energy Technology, the European Photovoltaic Technology Platform foresees grid parity also in Denmark before 2020. Some Danish module suppliers expect this to happen much sooner for BIPV, and also that a steep market increase is to be expected.

From a technical point of view, a share of at least 10% PV power by 2050 will fit well into the Danish energy system. Residential rooftops in Denmark are to a great extent directed east and west, and even though a 20% efficiency penalty for such installations is expected, they benefit from the improved generation in the mornings and evenings, when demand peaks. Hence a large fraction of Danish rooftops may potentially be utilised as platforms for PV.

Although this chapter does not cover solar thermal heating in details, it must be mentioned that centralised solar thermal heating plants have become a great success in Denmark. Some of the largest installations in the world are Danish, and they feed hot water directly into the well-developed district heating systems in a number of Danish communities. Recently, a large-scale experiment with geological seasonal heat storage has commenced. According to the Danish District Heating Association, and www.solvarmedata.dk, more than 100,000 square metres of solar thermal collectors are installed in central heating plants. The typical annual energy production is in the range of 400-500 kWh/m^2, corresponding to a thermal conversion efficiency of about 40%.

On the further perspective towards 2050 for solar thermal heating in Denmark, the vision of the Danish Solar Cell Association is identical to the European vision defined by the European Solar Thermal Technology Platform (ESTTP) in their 2030 vision: Solar thermal energy systems will provide up to 50% of low-temperature heating and cooling demand.

Conclusions

Solar energy is an available resource for heat and electricity production throughout the world. Our technical ability to utilise this resource has improved dramatically in recent years, and it is hard to imagine a society that by 2050 will not rely on the sun for a large share of its heat and power needs. The IEA currently predicts that the PV and CSP technologies will each cover 11% of global electricity demand by 2050.

Both PV and CSP have the potential to generate electricity at a competitive price compared to other generating technologies. Over the next ten years, incentive mechanisms are needed to support the build-up of market demand, production capacity and the technological advances that will secure production cost reductions.

PV is by nature a distributed generation technology, whereas CSP is a centralised technology; hence their deployment will follow very different routes. It is traditional – as we do in this chapter – to treat PV and CSP together because they rely on the same resource. However, the fact is that PV is unique among electricity generation technologies in that its distributed nature allows it to be integrated with human settlements, both urban and rural. The deployment of PV will be market-driven, especially when grid parity is reached in the residential, commercial and utilities sectors.

Practical PV is expected to include off-grid, residential, commercial and large-scale utility installations, of which residential uses will account for almost half. In certain urban areas – “solar cities” – PV and solar thermal energy can become the major sources of electricity, cooling and heating. As regards the challenges of energy storage and integration with smart grids, PV has much in common with wind power. Currently, local battery storage is used only for small electronics and off-grid applications, where overall energy efficiency is not an issue. For grid-connected PV, where overall efficiency is vital, there is currently no good way of storing large volumes of electricity.

CSP, on the other hand, faces issues common to most centralised electricity generation technologies. CSP relies on direct sunshine, which is often most abundant in desert areas a good distance from large urban centres. For that reason, the future deployment of CSP will require new electricity transmission systems. In nations with direct solar resources – the south-western USA, Australia, southern Europe – the political decision to deploy CSP is relatively simple. Other areas such as north Africa and central Asia have enough sunshine, but would need to export their electricity to Europe or Russia. The deployment of CSP will therefore be driven by politics as well as markets.

Many CSP systems separate the harvesting of thermal energy from the generation of electricity. This allows the plant to store thermal energy and to augment electricity generation with other energy sources; today's commercial CSP plants include backup capacity from burning fuel. Hybrid systems combining heat storage and the facility to burn fossil, biomass or even solar fuels allow for a 100% firm supply and potentially a 100% sustainable supply.

6
Wind energy

Peter Hauge Madsen and Flemming Rasmussen, Risø DTU, Denmark; John O. Tande, Sintef, Norway; Gijs van Kuik, Delft University, Netherlands

Introduction

The use of wind energy to generate electricity for the grid is quite a recent phenomenon following the modern development of wind energy starting in the late 1970s in the wake of the oil crises. Since then, wind energy has grown at spectacular rates thanks to concerns about energy security, environmental protection and climate change, and economics.

Thus, over the past 25 years global wind energy capacity has doubled every three years, corresponding to a tenfold expansion every decade. By the end of 2009, global installed wind capacity was approximately 160 GW and in 2010 is expected to produce more than 331 TWh, or 1.6% of global electricity consumption. Approximately 2% of the capacity installed during 2009 was offshore, bringing total offshore capacity to 2.1 GW, or 1.3% of total global wind energy capacity.

Future developments for wind power are described in the advanced scenario of the 2008 report by the Global Wind Energy Council (GWEC) [1], by the German Aerospace Centre (DLR) [2], and in the 2008 report to the IEA by the Risø DTU National Laboratory for Sustainable Energy [3]. These suggest that global wind energy penetration could be 10% by 2020, 20% by 2030 and 25-30% of electricity demand by 2050. These scenarios are based on growth rates of 27% in 2008, declining to 22% in 2010, 12% by 2020 and 5% by 2030. Targets of this order are realistic, and the available wind resource is not the limiting factor: Current global electricity consumption corresponds to that generated by a wind farm measuring 1,000 kilometres square. Long-term plans should therefore be based on these growth rates.

The huge potential of wind power, the rapid development of the technology and the impressive growth of the industry justify the perception that wind energy is changing its role to become the future backbone of a secure global energy supply.

Between the mid-1980s, when the wind industry took off, and 2005, wind turbine technology has seen rapid development, leading to impressive increases in the size of turbines, with corresponding cost reductions.

From 2005 to 2009 the industry's focus seems to have been on increasing manufacturing capacity, meeting market demand and making wind turbines more reliable. The development of new and larger turbines to some extent stagnated, and costs even rose due to high demand and rising materials costs.

We believe, however – and this is supported by recent trends – that the next decade will be a new period of technology development and further scale-up, leading to more cost-effective, reliable and controllable wind turbines and new applications. This is partly due to increased international competition, but also because the industry is increasingly dominated by high-technology international companies. The move to install more capacity offshore also favours larger wind turbines and encourages new ways of thinking.

Finally, there is an increasing awareness that renewables in general, and not least wind energy, will come to play a major role in the global energy supply as oil and gas are phased down in the period towards 2050. The cost of power from coal will also increase because of the need for carbon capture and storage.

In this chapter we discuss the current status of wind power and its prospects up to 2050, including both existing and emerging technologies.

Wind 2010: resource, deployment and technology

Studies of the exploitable wind resource [1], [4], [5] demonstrate that wind energy is a practically unlimited and emission-free source of energy, of which only a tiny fraction is currently being exploited.

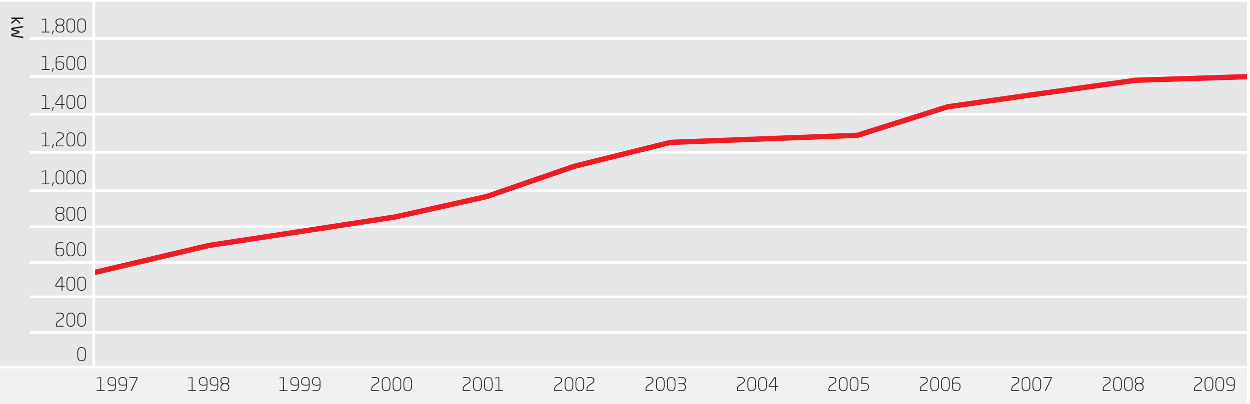
While the estimates differ by almost an order of magnitude, even the most conservative, such as the 2008 estimate by REN 21 [5], show that the world's expected electricity consumption in 2050 of 113-167 EJ/yr (31,000-46,000 TWh/yr) could be delivered by wind energy several times over. The potential of onshore wind is thus almost 400 EJ/yr (111,000 TWh/yr), even with conservative assumptions about resource and land availability.

Most forecasts predict an eventual fall in growth rates, and following the financial crisis that began in 2008 it seemed likely that future growth would be slower than in that year, when cumulative installed capacity grew by 30% to 122 GW. This did not happen in 2009, however: instead, cumulative installed capacity grew by 31% to 160 GW.

The average cumulative growth rate over the past five years has been 27.3%. While in the USA and many other countries the industry was encouraged by stimulus packages, the main growth came from China, which in 2009 installed almost 14 GW. In this light, assumed growth rates of 10-20% for the next 20 years do not seem overly optimistic.

Until the 1990s, a great variety of different wind turbine concepts were tested and manufactured. These included turbines with one or two blades, stall-controlled designs, and vertical-axis turbines. In contrast, the typical wind turbine being installed today (2010) is a three-bladed, upwind, pitch-controlled, variable-speed machine connected to the electricity grid, with a capacity of 1.1-1.5 MW in Asia and 1.9-2.3 MW in Europe and the USA [6].

Figure 17
Growth in the global average size of installed wind turbines (WTGs). Source: BTM Consult ApS - March 2010. Source [6]



Mainstream technological development for land-based utility-scale wind turbines is now characterised primarily by scale-up (until 2005 the size of turbines doubled every five years (Figure 17). But though most wind turbines now look similar on the outside, manufacturers have introduced new materials, control principles, generator and converter technologies. Together with the technical challenges associated with scale-up, these developments have called for advanced research in a number of fields.

Over the past 20 years, average wind turbine capacity ratings have grown continuously; the largest proportion of land-based utility-scale wind turbines installed globally are rated from 1.0 MW to about 3.6 MW. The largest wind turbines are installed offshore, notably in the UK and Denmark, while land-based turbines in Asia are generally smaller, at around 1.0-1.4 MW. This suggests that further development will happen in several tracks, including accelerated scale-up for offshore turbines and smaller installations on land, sized appropriately for the application and local infrastructure.

Development towards 2050

Table 4 summarises the expected development of wind energy technology and its penetration of the electricity supply. We will expand on this information in the sections to follow.

Industry trends and costs

Industrial wind turbine technology was originally developed primarily by small companies in Europe and the USA working closely with research organisations. Though this development gradually attracted the attention of established industrial manufacturers, the original small companies had made considerable progress in diversification, turbine scale-up and deployment before some of them were taken over by multinational energy companies (GE, Siemens, Alstom), while others (Vestas) grew by merging with competitors of similar size.

Table 4
Summary of wind energy technology developments up to 2050

	2010	2020	2030	2050
% global electricity generated from wind	1.7%	10%	20%	30%
Known technology	3-bladed, geared drive train, converter (98.5% of generating capacity), 2–3 MW onshore (1.5%) 3–5 MW offshore, fixed foundation of 15–30 m depth	3-bladed, 50/50 geared drive train and direct drive, converter (83%) 2–3 MW onshore (15%) 6–10 MW offshore, fixed foundation of 25–50 m depth (<1%) <50 kW onshore	3-bladed, 25/75 geared drive train and direct drive, converter, advanced sensors and control 2–3 MW onshore	3-bladed, 20/80 geared drive train and direct drive, converter 2–3 MW onshore
Emerging technology	Demo floating wind turbine	(1%) 6–10 MW offshore, floating foundation		
New concepts	Small wind turbines in the built environment	Demo combined wind-wave systems Demo offshore vertical-axis turbine Demo high-altitude WT		
System integration	Hourly production forecast Grid code compliance Wind farms operated as power plants	Offshore grid development Increased use of hydro with pumped storage for balancing		

In Asia, new players initially licensed technology from Europe, but quickly went on to develop their own wind turbines.

Wind turbines are based on a unique combination of technologies, and are gradually becoming increasingly sophisticated. The amount and diversity of research carried out will determine how far wind turbine technology will develop.

Wind turbines are complex designs, and in technical terms there are no limits to how far they can be improved.

However, diminishing returns may cause the industry itself to limit future technological improvements. Whether or not this happens depends very much on the future structure of the industry, and the ability of turbine manufacturers, R&D specialists and legislators to work together to ensure that the industry remains vital, dynamic, innovative and competitive. As the motto of Roskilde University puts it, in tranquillo mors, in fluctu vita ("in stillness death, in movement life").

We can imagine four existing industries which a future wind turbine industry might come to resemble:

"Shipbuilding" Large structures, but relatively low-tech: probably the worst case, as it would discourage investment in new technology.

"Aerospace" A handful of global wind turbine manufacturers supported by a larger number of niche suppliers. This scenario describes the wind industry until five years ago, since which time many new players have entered the scene.

"Automotive" R&D involves the component suppliers as well as the wind turbine manufacturers themselves. This scenario has the attraction of creating widely used standard components which make good use of common R&D effort.
"Power stations" Component manufacturers supply contractors who in turn are project-managed by large energy companies. This scenario could make it hard to exploit the full benefits of mass production.

The overall goal is to make wind energy steadily more cost-effective and reliable as a future large-scale global energy source. It is likely that the future wind industry will have elements of all four scenarios listed above, but of these, the third ("automotive") offers perhaps the best opportunities for innovation and technological development. We certainly see opportunities for component suppliers to play a larger part in the development process.

Up to 2005, the industry saw learning rates of 0.17-0.09 (in other words, a doubling of cumulative installed capacity reduces the cost of electricity per kWh by 9-17%) (Figure 18) [3].

From 2005 to 2009, installation was limited by manufacturing capacity, higher material costs and higher margins for manufacturers, with the industry focused on increasing production capacity and improving reliability.

In future, we expect changes in industry structure and increased competition to accelerate technological development, and we see no reason to expect a learning rate of only 10% as assumed in [3] and Figure 18.

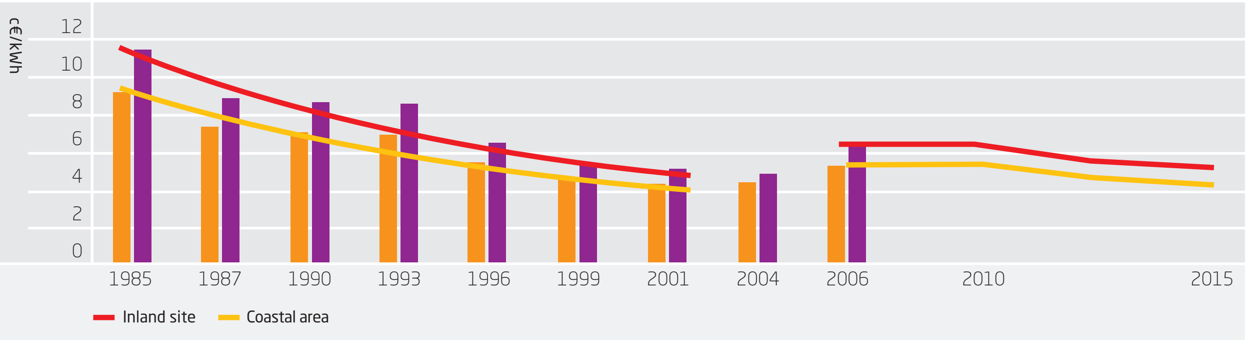
Technology trends

Mainstream technology

The 30-year development of wind energy technology, with its focus on reducing the cost of energy, has seen the size of the largest turbines increase by a factor of 100, from roughly 50 kW to 5 MW.

This is in spite of a theoretical limit to the maximum size of a wind turbine. As a wind turbine increases in size (while keeping the same proportions) its energy output increases as the square of the rotor diameter, but its mass increases roughly as the cube of the rotor diameter (the "square-cube

Figure 18
Using experience curves to forecast wind energy economics up to 2015. The costs shown are for an average 2 MW turbine with a present-day production cost of euro ¢6.1/kWh in a medium wind regime. From [3]



law”). As the mass increases, the mechanical loads imposed by gravity increase even faster, until the point where the materials available are not strong enough to withstand the stresses on the turbine.

So far, engineers have avoided the limits of the square-cube law by steering clear of direct geometrical similarity, using materials more efficiently, and using stronger materials. Perhaps most importantly, designers have tailored the responses of turbines ever more carefully to the conditions under which they operate, and this remains one of the main ways of reducing the cost of energy from future turbine designs.

Issues of geometry notwithstanding, several factors favour larger turbines. However, it seems fair to assume that at some point the cost of building larger turbines will rise faster than the value of the energy gained. At this point scale-up will become a losing economic game.

As a result, it is important also to look at other ways of cutting costs. This can be done, for instance, by introducing cheaper technology or by increasing the amount of energy captured by a rotor.

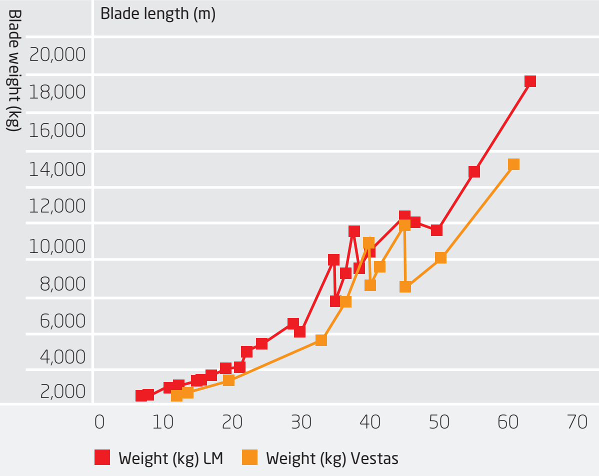
Conventional wind turbines use gears to match the slow speeds of the blades and hub to the higher speeds required to drive a standard induction generator. It has been known for many years that a multi-pole generator, which can run at slower speeds, offers the chance to eliminate the gearbox. Early multi-pole generators were large and heavy, but newer permanent-magnet designs, in which the rotor spins outside the stator, are compact, efficient and relatively lightweight. The next generation of multi-MW gearless wind turbines is expected to create a step change in the industry, followed by further gradual cost reductions as with previous turbine types.

Lightweight blades

As described above, geometrical similarity says that as blade length increases, blade weight should increase with an exponent of 3 (a cubic law). In fact, several studies have shown that over recent decades the actual exponent has averaged around 2.3, and for the most recent blade designs it is 2.2 or 2.1 (Figure 19).

Many factors have aided the move to lighter blades, of which the most important has been the development of blades that are much thicker than their predecessors, especially near the hub. Because they are stiffer at the point where the loads are highest, these new blade designs make more efficient use of materials and are lighter overall. This principle can continue to produce even larger blades that beat the square-cube law as long as it is backed by the necessary R&D into better design methods, new materials such as carbon fibre, and advanced manufacturing techniques.

Figure 19
New technology and better design means that new blades are much lighter than simple geometry would predict, based on the weight of older blade designs



One potential drawback of using thicker airfoil shapes at the blade root is a loss of aerodynamic efficiency. The answer may lie in high-lift designs such as multiple airfoils for use at the blade root (Figure 20), or the newly developed “flat-back” airfoil, which can maintain lift even when it is very thick.

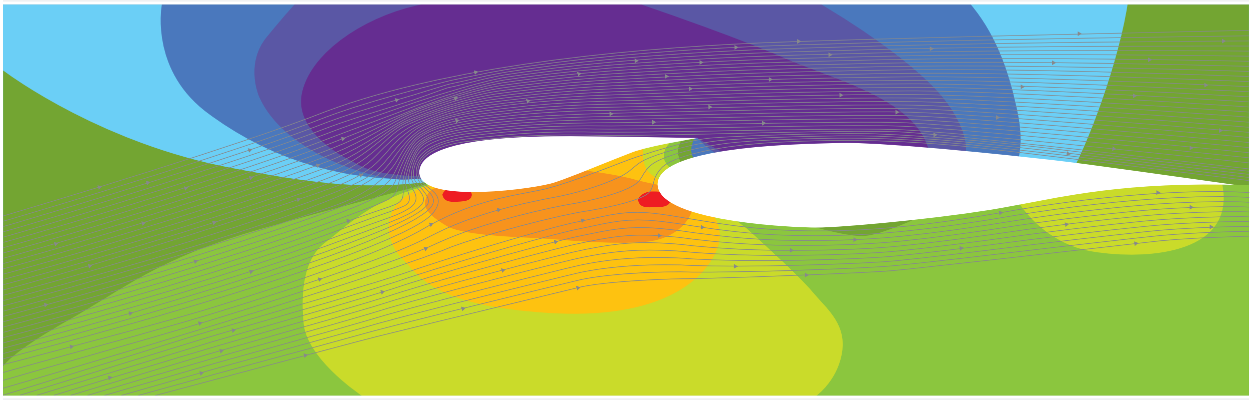
Another way of cutting the cost of wind energy is to increase blade length while reducing the fatigue load on the blade. There can be a big payoff in this approach because material consumption is approximately proportional to fatigue loading.

Fatigue loads can be reduced by controlling the blade’s aerodynamic response to turbulence. This is already done actively via the turbine’s pitch control system, which turns the complete blade, and future turbines may also feature movable control surfaces distributed along the blades.

An especially elegant idea is to build passive ways of reducing loads directly into the blade structure. Using the unique attributes of composite materials to tailor its structural properties, for instance, a blade can be built in a way that couples its bending and twisting deformations.

Another way of achieving this “pitch-flap” coupling is by building the blade in a curve so that fluctuations in the aerodynamic load produce a twisting movement which varies the angle of attack [7]. It should also be possible to vary the lift produced by the blade by altering the camber of the airfoil in response to flap-wise deformation, as birds’ feathers do. Such complicated blade motion will require a very good understanding of wind turbine aerodynamics and materials science.

Figure 20
Multi-element airfoil to enhance lift (CFD simulation, Risø DTU)

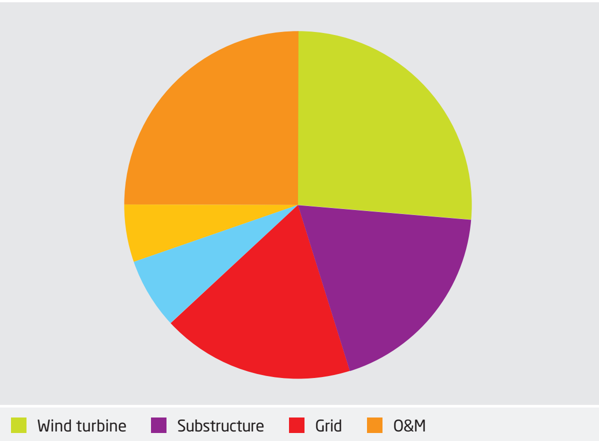


Innovative systems of trailing-edge control could considerably reduce the fatigue loads on blades. These are now being developed in projects involving European research institutions and industry, including the large EU-funded UpWind project.

As well as reducing loads, such advanced multi-control options could help to improve turbine performance and tune the turbine's operation to on-site conditions. For instance, a laser ranging (LIDAR) system mounted on the turbine could measure upstream wind speed and detect turbulence before it arrives at the turbine, giving an active control system more time to respond.

Indeed, aiming for cost reductions is not only a question of improving the rotor and generator as elaborated on here. The life-cycle cost of energy from an offshore wind farm comprises the wind turbines, installation and substructures, grid and O&M as the four dominating elements (Figure 21).

Figure 21
Example life-cycle cost of energy distribution for offshore wind farm. SINTEF Energy Research



Hence, for cost reductions to be achieved, a broad approach must be taken, addressing wind turbine technology, but also substructures, grid and O&M.

Emerging technologies

So far, most development efforts have been dedicated to an evolutionary process of scaling up and optimising the land-based, three-bladed standard wind turbines which first emerged as commercial products at the beginning of the 1980s.

To the original design have since been added individual blade pitch control, variable speed and other refinements to match the increasing size of the turbines; increasingly stringent performance and reliability requirements; and adaptations for use offshore.

Figure 22: Ideas for floating wind turbines: SWAY (l) and Hywind (r)

One example of a technical development is "negative coning", in which the blades point slightly forward; this increases the clearance between the blades and the tower, and also improves stability for very flexible blades. Such improvements are only possible when turbine engineering goes hand in hand with the development and application of advanced simulation and design tools. Without such tools, it would not have been possible to increase the size of wind turbines by a factor of 100 in 30 years.

Offshore wind power brings new opportunities, since offshore winds are generally stronger and steadier, but represents an even bigger challenge for turbine development, operation and cost optimisation. Operating conditions offshore are very different, so what is most cost-effective onshore may need a radical re-think for use out at sea. Figure 22 shows how future offshore turbines might diverge from their land-based counterparts.

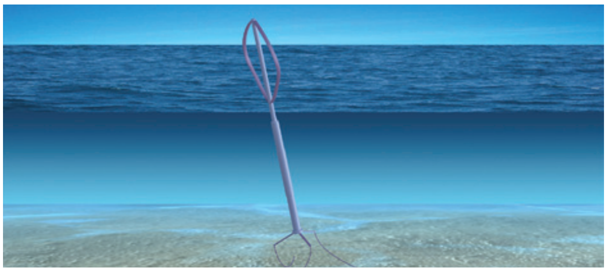


Figure 23: The Risø DTU vertical-axis floating wind turbine

New ideas offshore

The strength of the offshore market, and the very different conditions found offshore, make it likely that completely new types of offshore turbine may emerge. An example is the vertical-axis floating turbine illustrated in Figure 23.

Vertical-axis turbines have been tried and rejected for onshore use. The logic for using them offshore runs as follows:

Figure 24: The Poseidon demonstration project is a floating power plant which harvests both wind and wave energy

The need to install turbines in deep water, where foundations are expensive, makes floating turbines an attractive idea. But conventional horizontal-axis turbines carry a large amount of weight at the top of the tower (high "top mass"), and this can cause balance problems for floating turbines. Vertical-axis turbines have lower top mass and do not need to turn into the wind, so large floating versions may become attractive.

Another idea is to harvest energy from wind and waves at the same time (Figure 24). The shared supporting structure and infrastructure might create a symbiosis that could accelerate the development of reliable and cost-effective wave energy solutions.

High-altitude wind systems

Various arrangements of balloons, kites and other tethered airfoils have been proposed to take advantage of strong winds at greater heights than rigid turbine towers can reach.

There are two basic approaches: Either transmit mechanical energy directly to the ground, where it can generate electricity or be used in other ways; or generate electricity aloft and send power down through a tether.

Up to around 500 metres, wind speed increases with height.

From 500 metres up to 2,000 metres, however, wind power density[12] actually decreases slightly with altitude.

Above 2,000 metres, wind power density again increases monotonically with height.

The jet streams – narrow "corridors" of wind which move around at altitudes of 7-16 kilometres – are an order of magnitude faster than winds near the ground.

There may not be much benefit from going higher than 500 metres, therefore, unless we can place devices above 2,000 metres, or preferably in the jet streams.

Urban wind turbines

Small wind turbines and urban wind energy might seem just a curiosity in terms of their contribution to the energy supply, but this could change in future.

By 2050, our energy systems are likely to be much less centralised than at present, and people will be taking more responsibility for energy at a local level. These changed perceptions could make urban wind energy more attractive.

[12] Wind power density is a function of wind speed and air density. It reflects the fact that air density, and hence the amount of energy produced by a turbine at a given wind speed, falls off with altitude.

The challenge is to develop "urbines" that can be integrated cost-effectively into the built environment. Low sensitivity to turbulence and low noise are essential.

Wind power in context

We have shown above that the opportunities for wind energy are enormous; they expand still further if we take into account the predictability of wind energy when studying the economics of energy investments [9].

The report Wind Force 12 [10] is based on the realistic assumption that wind power will continue to grow in the next ten years as it has over the past ten. If this is so, by 2020 installed wind capacity will be increasing at 151 GW/yr, representing an annual investment of €75 billion. In this scenario, wind power will produce 12% of the world's electricity requirement by 2020, by which time it is assumed to be 30,000 TWh/yr compared to 18,000 TWh/yr today. The technological vision of Wind Force 12 is to make wind power 40% cheaper in 2020 than it was in 2000.

In 2000, global electricity production was 15,000 TWh/yr. This amount of power could be produced by a fictitious wind farm measuring 1,000 kilometres square. Such an array of turbines would fit into the Great Plains of the USA and still leave 98% of the land available for agricultural use. Supplying the world's total energy needs from wind would require an area around four times bigger, and generating 60,000 TWh/yr. For comparison, Wind Force 12 estimates the world's total exploitable onshore wind resource to be 53,000 TWh/yr.

Even with the predicted increases in energy demand by 2050, the idea of getting all the world's energy from wind is still realistic in terms of the geographical area needed. This would, however, require enormous changes in our systems for converting, transporting and storing energy.

Apart from its basic role in getting electricity from wind turbines to consumers, power transmission has an important part to play in balancing local fluctuations in wind power production against fluctuations in consumption. Europe is currently placing much emphasis on strengthening and extending the transmission lines between load centres and producers, including offshore wind power plants.

Other ways of balancing demand and production include wide geographical distribution of wind power plants, better forecasting of wind, demand management and electricity storage.

Conclusions

We believe that the development of wind energy has only just begun, with respect to both technology and application.

The past 30 years of R&D have established a firm foundation for wind power. While further R&D will certainly be necessary to reduce costs and fully exploit the great potential of wind, much of the earlier uncertainty about the feasibility of wind energy has now been dispelled.

The next decade is thus shaping up as a new period of technology development and further scale-up, leading to more cost-effective, reliable and controllable wind turbines and new applications for wind power.

Increased international competition is helping to reveal the great potential that exists for wind power technology and markets. The increasing dominance of the industry by high-tech global companies and the move towards offshore siting favours ever-larger wind turbines and opens up new perspectives.

Finally, there is increasing awareness that renewables in general and wind energy in particular will play a major role in the global energy supply as oil and gas are phased out in the period towards 2050, and the cost of coal-based energy increases, not least due to the cost of carbon capture and storage.

Wind energy has the potential to supply 30-50% of our electricity, and to do this cost-effectively.

7
Hydropower

Jørgen Fenhann, Risø DTU, Denmark; Jens Peter Kofoed, Aalborg University, Denmark

This chapter gives an overview of the various forms of hydropower: conventional hydropower, marine currents, tides, power from salinity gradients, ocean thermal energy conversion and wave power.

Hydropower

Since 1960, hydropower has expanded globally from about 1,200 TWh in 1970 to more than 3,200 TWh in 2008 (ENERDATA), and is expected to increase to 4,810 TWh in 2030 (IEA 2008).

At present, OECD and non-OECD countries produce roughly equal amounts of hydroelectricity. Within the OECD, many of the best sites have already been exploited, and future growth is therefore expected to happen mostly in developing countries. Hydropower has little potential in the low-lying terrain of Denmark.

Hydropower is a mature technology close to the limit of efficiency; most components have been thoroughly tested and optimised over many years. However, the efficiency of many older hydropower turbines could be improved by retrofitting new equipment (UNWWAP 2006). About 75% of the world's 45,000 large dams were built for irrigation or flood control; only 25% are used for hydropower or as multipurpose reservoirs (WCD 2000). There is thus a significant potential for increased hydropower generation at many of these dams. In fact, 7% of the hydropower projects supported by the Kyoto Clean Development Mechanism (CDM) are adding power production to existing dams.

Marine current and open tidal power

Marine currents carry a lot of kinetic energy, part of which can be transformed into electricity by submarine turbines. Those are more compact than wind turbines, simply because water is almost a thousand times denser than air.

The physical characteristics of marine currents are well known. The power available is about 4.1 kW/m^2 for a current speed of 2 m/s, and 13 kW/m^2 for a current of 3 m/s. Capturing the energy of currents in the open ocean requires essentially the same basic technology as for tidal flows, but some of the infrastructure will be different. In deep-water applications, for instance, fixed bottom support structures will be replaced by anchors. In addition, ocean current systems can have larger rotors since they are not constrained by channels.

MCT/SeaGen has successfully deployed a 1.2 MW installation at Strangford Lough in Northern Ireland. This takes the form of a turbine with two rotors, each of which has two blades, mounted on a cross-beam supported by a single pile.

The Irish company Open Hydro has been testing a 250-kW machine at the European Marine Energy Centre in the Orkney Islands off northern Scotland. Around ten other new marine current devices have entered the field recently, and a number of large projects are planned over the next five years, the biggest being the 300 MW Lunar Energy installation in South Korea by 2015 (Bahaj 2009).

Barrage tidal power

Tidal energy is driven by the gravitational pull of the moon. The periodic nature of the tides implies that tidal power plants will be discontinuous, generating for only four or five hours in each 12-hour tidal cycle. However, tidal power plants can be designed to be reversible, so that during periods of low electricity demand they can store energy by using power generated elsewhere to pump water back against the tidal flow.

The only large, modern example of a tidal power installation is the 240 MW La Rance plant in France, built in the 1960s and representing 91% of world tidal power capacity. An 18 MW tidal barrage was commissioned in 1984 at Annapolis Royal in Nova Scotia, Canada. China has seven small tidal plants with a total capacity of over 5 MW, of which the largest is the 3.2 MW Jiangxia plant. A 400 kW tidal plant at Kislo Gubskaya in Russia has been upgraded to 1.5 MW.

Numerous studies have been completed for promising locations with unusually high tidal ranges, such as the Severn estuary in the UK, where proposals from 0.625 GW to 14.8 GW are being investigated. Several other potential sites in the UK are also being considered. The 254 MW Sihwa Tidal Power Plant in South Korea has been registered under the Kyoto Clean Development Mechanism (CDM) and is expected to start up in 2010. Other countries, including the USA, India, Mexico and Canada, have reported potential for new tidal projects.

Salinity gradient

Where fresh water from rivers runs into salty seawater, osmosis based on the difference in salt concentration between the two liquids could be used to generate power.

Depending on the salt concentration of the seawater, a pressure of 24-26 bar will exist across a membrane separating the seawater from the fresh water. This pressure difference can be used to drive a generator.

The global generating potential has been estimated at 1,600 TWh/yr, of which 170 TWh/yr is in Europe (Scråmestø, Skilhagen, 2009).

The first osmotic power plant in the world, built by Norwegian power company Statkraft, started operating in October 2009 at Tofte, near Oslo. Statkraft will use this working prototype to develop a 1-2 MW plant within two to five years.

Ocean thermal energy conversion

Ocean thermal energy conversion (OTEC) systems use the oceans' natural thermal gradient – the fact that layers of water have different temperatures – as a source of power. As long as the temperature between the warm surface water and the cold deep water differs by about 20°C, an OTEC system can produce a significant amount of power.

Considerable work on OTEC was done after the oil price shocks of the 1970s. One example is a shore-based 100 kWe plant tested by Japan in 1981 in the Republic of Nauru in the Pacific Ocean. This plant employed a cold-water pipe laid on the sea bed at a depth of 580 metres. OTEC research waned during the following two decades, but recently there has been some revival of interest.

OTEC is useful not only for electricity production but also for desalination and cooling. Desalination was demonstrated successfully in 2007 by India's National Institute of Ocean Technology on the floating barge Sagar Shakti, which produced 1,000 m^3/day of drinking water.

Cooling using seawater air conditioning (SWAC) is the only technology based on the thermal properties of the ocean water column to have reached commercial maturity. It is essentially a land-based technology that relies on easy access to cold water from population centres onshore. Many SWAC systems are currently being considered; the largest system is being planned by Honolulu Seawater Air Conditioning, while in French Polynesia existing projects have already proved successful (Nihous 2009).

Wave power

Wave energy can be seen as stored wind energy. After the wind has dropped, for instance, waves normally continue for a further six to eight hours. Wave power could therefore form an interesting partnership with wind power when energy storage is needed.

In the long term, wave power could make an important contribution to the world's energy demand if it can be made technically and economically feasible. A potential 2,000 TWh/yr, or 10% of global electricity consumption, at a cost of €0.08/kWh has been predicted by Ngô et al. (2006). The global net potential resource (excluding areas with an average wave power level of less than 5 kW/m and areas which may experience ice coverage) has been estimated to be 3.0 TW (or 26,000 TWh/yr) (Mørk et al. 2010). Thus, wave power holds a vast as yet unutilised potential. Furthermore, wave power machines have the advantage of being quiet and unobtrusive.

Oceanic waves far offshore contain enormous amounts of energy: Annual average power levels in good offshore locations (mostly at high latitudes) are 20-70 kW/m. Seasonal variations are generally larger in the northern than in the southern hemisphere, making the southern coasts of South America, Africa and Australia particularly attractive (Falcão 2009).

Countries investigating wave power include Japan, the USA, Canada, Russia, India, China, Portugal, Norway, Sweden, Denmark and the UK. At present, the front-runners are Portugal and the UK. A study shows that 335 kilometres of Portugal's coastline is available for wave power because it lies outside zones set aside for fisheries, navigation, environmental protection and military activity (Wave Energy Centre 2007).

Unlike the technology used for large wind turbines, there are very many ways to harvest wave energy. More than 1,000 wave energy conversion techniques have been patented worldwide, and new ideas are being invented faster than old ones are abandoned. Despite their great number, however, wave power devices fall into just three basic types: oscillating water columns (OWCs), oscillating bodies and overtopping devices.

Pelamis Wave Power, based in Edinburgh, Scotland, has developed the 750 kW Pelamis wave energy converter. This jointed mechanical snake, 150 metres long and 3.5 metres in diameter, floats near the surface and generates power by flexing in the waves.

Three Pelamis units with a total capacity of 2.25 MW were tested in 2008 at the world's first commercial wave farm off the Portuguese coast. After barely two months, however, the equipment had to be towed back to shore because of buoyancy issues and a shortage of funds – showing how difficult it is to set up a viable wave power system.

Aquamarine Power has developed the Oyster, a hinged metallic shell which sits on the sea floor at depths of 10-12 metres. As waves wash over it, the Oyster opens and closes, and this action is used to pump pressurised water to an onshore generator. A full-size prototype (300-600 kW) has been powering 9,000 homes in Orkney since November 2009 (Baras 2010).

The Wave Dragon (Figure 25) is a floating overtopping wave power device developed in Denmark. A 1:4.5-scale prototype has been on test at the Danish test site at Nissum Bredning since 2003. Wave Dragon's backers plan a 4-7 MW demonstration project in Wales, but money has proved hard to find in the current economic climate. They are therefore beginning to explore other opportunities such as a smaller demonstration project in the Danish North Sea.

Figure 25: Wave Dragon 01:04.5 prototype during testing in Nissum Bredning (© Earth-vision.biz)

The Wave Star generator (Figures 26 and 27) uses floats which can lift out of the water to reduce the risk of damage during storms. A 24-metre-long 1:10 scale model, with floats 1 metre in diameter, was installed at Nissum Bredning in April 2006. A Wave Star unit with two floats, each 5 metres in diameter, has been on test near the port of Hanstholm in western Denmark since 2009.

The first commercial 500 kW Wave Star is scheduled for testing in 2011-12. Within a few years the plan is then to double the dimensions, allowing the Wave Star to handle waves that are twice as large and boosting the maximum power output to 6 MW (Wave Star 2010).

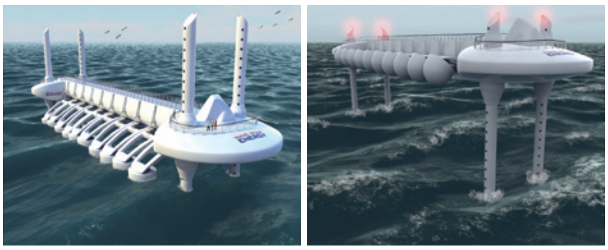


Figure 26: Artist's impression of the full-scale Wave Star machine

At the moment, wave energy systems of many types are at several stages of development, and it is not clear which technologies will win.

For some time, the Wave Dragon and Wave Star have formed the vanguard of wave power in Denmark. In the past few years, however, other wave power projects, including Poseidon, Wave Plane, LeanCon and DEXA, have begun to make progress with large-scale tests under real conditions.

Figure 27: The two-float Wave Star prototype at Roshage, Hanstholm, Denmark

Most successful wave power projects have required substantial financial support from governments. Denmark has been working on wave energy for about 20 years now. From 1998 to 2002, the Danish Energy Authority contributed DKK 40 million through the Danish Wave Energy Programme (DWEP). This accelerated the development of wave energy in Denmark and established a rigorous four-step process to identify the best technologies.

The first phase of the programme screened up to 50 potentially promising devices. Some 10-20 of these made it to a second phase of feasibility and parametric studies. The most successful went on to a third phase of testing in protected marine environments such as Nissum Bredning. Several of these, including Wave Star and Wave Dragon are now preparing for phase four: full-scale testing.

Later programmes such as ForskEL and EUDP have followed the DWEP four-stage approach (Kofoed & Frigaard 2009).

Denmark is also promoting the entire wave energy industry as well as individual wave power technologies. The Danish Council for Strategic Research has granted DKK 20 million for a five-year project (a strategic alliance) on the structural design of wave energy devices led by the Wave Energy Research Group at Aalborg University (www.sdwed.civil.aau.dk). The project has a total of 12 alliance partners. The main partners include, besides Aalborg University, DTU and DHI.

Another important initiative is the Danish Wave Energy Centre (DanWEC) which has been established in Hanstholm (www.danwec.com) as a non-profit organisation by the local harbour, the municipality, the region and Aalborg University. Its main aim is to facilitate the demonstration of wave energy technologies and help companies bring their products to market. Funding for DanWEC is being sought, and an application for the Green Labs programme is being prepared.

Conclusion

Wave power has the technical potential to provide between one-third and two-thirds of Denmark's current electricity consumption. However, such a large amount of wave power would probably require an unreasonably large area of generators in the Danish part of the North Sea. An ambitious yet realistic goal for wave power could be around 5% of Danish electricity by 2050.

If Denmark can develop commercial wave power technologies, there is also a vast export potential. Wave power could one day provide at least 10% of the world's electricity, or even more if we are prepared to pay higher power prices.

The commercial development of wave power technologies is still generally at an early stage, but internationally there are at least a handful of companies who may soon have marketable products. The industry leader is currently Pelamis in Scotland, which recently launched a second-generation full-scale machine. Other designs such as the Oyster from Aquamarine Power, OPT in the USA and Wave Star in Denmark are making good progress towards commercialisation.

8
Bioenergy

Kim Pilegaard, Henrik Hauggaard-Nielsen, Klaus Breddam, Jens Ejbye Schmidt and Ulrik Birk Henriksen, Risø DTU, Denmark

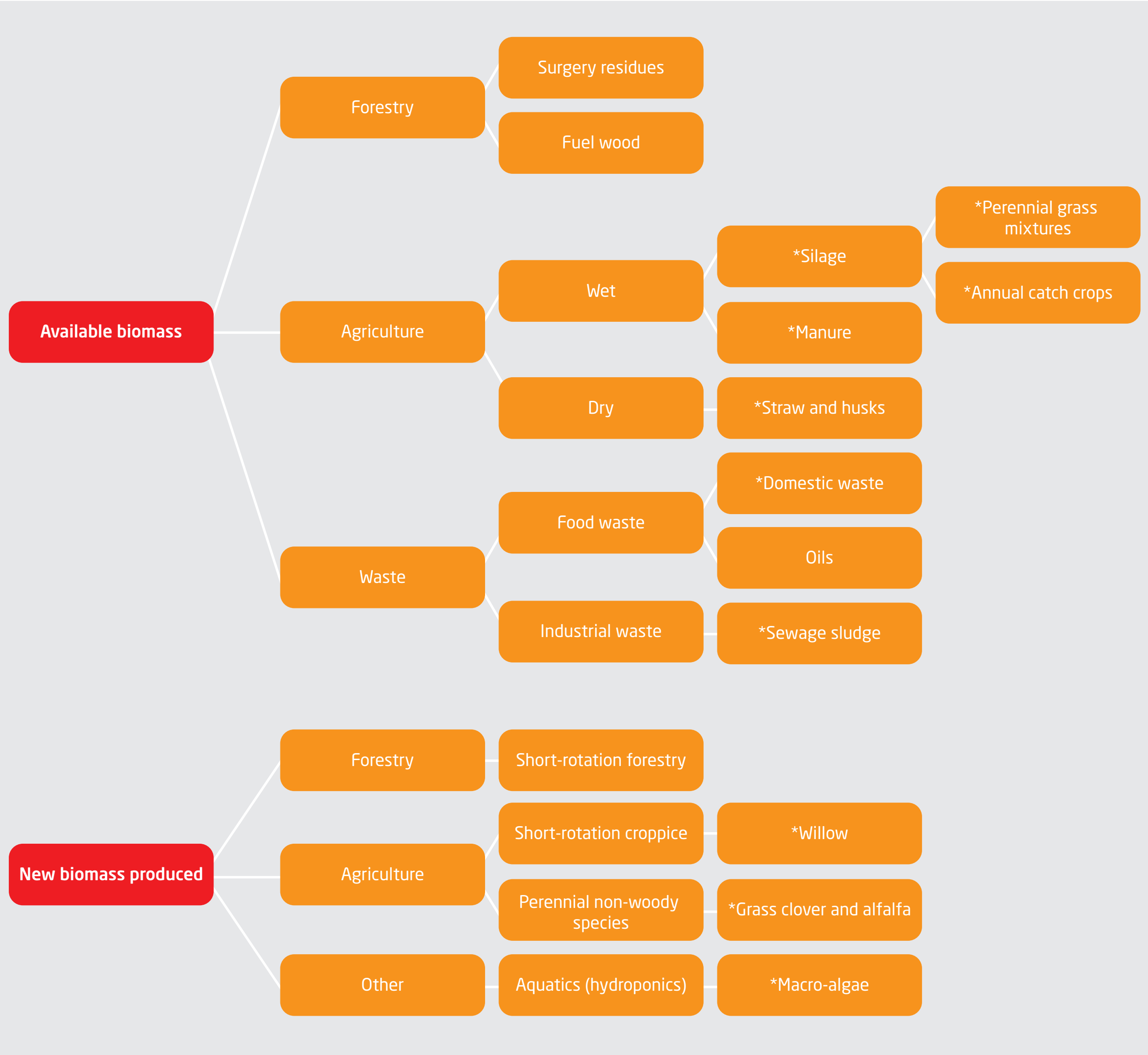
The potential of bioenergy and the available technologies have been considered in detail in previous Risø Energy Reports, notably Energy Report no. 2 (2003) which dealt exclusively with bioenergy. The following is therefore not a fully comprehensive account of potentials and barriers for bioenergy, but should be regarded as an update focusing on recent developments and concerns.

Biomass resources

The current energy supply is dominated by fossil fuels. Biomass is the most important renewable energy source with a contribution of approximately 10% of the total energy supply (Durnberg et al. 2010), and this share is expected to increase over the coming years. However, such a development where biomass is removed from forest and agricultural ecosystems can have negative impacts (Faaij 2008), e.g. changing land-use patterns can influence GHG emissions and put additional pressure on the biodiversity of farmland and forests as well as soil and water resources (EEA 2006).

Growing demand for food from an increasing world population, impacts of climate change and more sensitive global markets have resulted in a tendency of rising prices on biomass resources and fuels (Dam et al. 2008). Whether prices

Figure 28
Sources of already available (top) and potential new (above) biomass for sustainable bioenergy



* The feedstock used in present Risø DTU bioenergy research activities

will increase or decline in future is obviously rather speculative to conclude on, but rising price fluctuations are expected.

Biomass includes a wide range of species and by-products from forestry, agriculture, and municipal and industrial waste (Figure 28). It includes crop residues, forest and wood process residues, animal wastes including human sewage, municipal solid waste (excluding plastics and inorganic components), food processing wastes, purpose-grown energy crops and short-rotation forests (IEA 2007). In this chapter we sometimes use the industrial term "feedstock" to reflect this diversity.

The relevance and availability of biomass feedstock in different parts of the world will vary according to climate, agricultural and forestry practices, available technologies, and especially land availability and quality (EEA 2006; FAO 2008; IEA 2007). It is estimated that the land currently devoted to energy crops globally is to the order of 25 million hectares, representing 0.2% of the world's total land area and 0.5-1.7% of all agricultural land (Ladanai and Vinterbäck 2009).

It is beyond the scope of this chapter to compare the many studies on the potential for biomass as a source of energy, but Table 5 shows one example, taken from the comprehensive publication by Hoogwijk et al. (2003). This shows that the range of estimates for energy from biomass within the next 50 years or so varies widely, from 33 exajoules (EJ)/yr to 1,130 EJ/yr.

The upper end of this range matches the highest global energy consumption estimate – around 1,050 EJ/yr in 2050 – from the study by Smeets et al. (2007). On this basis, it would seem possible for biomass to cover all our future energy needs, but that is not deemed realistic. Factors affecting biomass production include (Hoogwijk et al. 2003):

- future demand for food, determined by population growth and changes in diet;
- the types of food production system that can be adopted worldwide over the next 50 years;
- productivity of forest and energy crops;
- increasing use of biomaterials (see below);
- availability of degraded land; and
- competition for land use, such as surplus agricultural land taken up by reforestation.

Furthermore, it is regarded as vital for the sustainability of future biomass production strategies to include potential ecological impacts, e.g. that no additional pressures on biodiversity, soil and water resources are exerted compared to a development without increased production of biomass for bioenergy purposes (EEA 2006).

Biomass currently used as a source of useful materials includes wood for building, rubber and cotton. In future, biomaterials are expected to expand into new applications such as carbon-neutral alternatives to coal and coke in the iron and steel industry, and feedstock for the production of chemicals, plastics, paint and solvents.

Narrowing the focus to Europe, the European Environment Agency (EEA) calculated how much bioenergy Europe could produce by 2030 without harming the environment (EEA 2006). The conclusion was that bioenergy from agriculture, forestry and waste could yield around 12 EJ/yr by 2030 (8 EJ/yr in 2010), subject to certain assumptions:

- at least 30% of agricultural land is dedicated to "environmentally oriented farming";

Table 5
Contributions of different land-use categories to global biomass potential for energy. Source: Hoogwijk et al. 2003

Land-use category	Notes	EJ/y
Biomass on surplus agricultural land	Area 0–2.6 Gha; yield 10–20 t/ha/yr	0–998
Biomass on degraded land	Area 430–580 Mha ; yield 1–10t/ha/yr	8–110
Agricultural residues	Estimate from various studies	10–32
Forest residues	A significant fraction comes from natural forest reserves; estimate from various studies	10–16 (+32 from biomaterial waste)
Animal manure	Estimate from various studies	9–25
Organic waste	Estimate from various studies	1–3
Biomaterials	Depends on demand; area 416–678 Mha as surplus and degraded land	83–116
Total		33–1,130

- extensively cultivated agricultural areas are maintained as such;

- approximately 3% of intensively cultivated agricultural land is set aside to establish ecological compensation areas;

- bioenergy crops with low environmental impact are used;

- currently protected forest areas are maintained; and

- ambitious waste minimisation strategies are applied.

As a result, by 2030 the EU25 countries could get 15-16% of their projected primary energy requirements from biomass, compared to around 5% at present.

Around 33% of this 2030 biomass total would come from waste, and around 19% from forestry, both sources changing relatively little over time. As a result, most of the growth would come from agriculture, whose contribution would triple, from 2 EJ/yr in 2010 to 6 EJ/yr in 2030. By then, agriculture would be providing about 47% of Europe's energy-related biomass, and this would require 12% of all agricultural land.

The necessary transformation in Europe's agricultural sector would probably happen through both productivity increases and an increase in the land area dedicated to growing biomass. The first row of Table 5, for example, shows that biomass from surplus land could provide up to 998 EJ/yr worldwide. Over time, farmers are expected to find that high fossil fuel prices and increases in carbon prices make bioenergy feedstock competitive with traditional wood products and food crops (EEA 2006).

Independently of region, soil fertility and the bioenergy technologies available, increased bioenergy demand can affect both extensive farmland and grassland by shifting production from existing crops to biomass for energy. The alternative, which is to harvest biomass from marginal land, may have detrimental effects on soil carbon stocks, nutrient cycling, soil fertility, pests and diseases because it disturbs complex communities of animal, plant and microscopic life above and below ground. Biomass production for energy purposes on marginal land needs to meet both economic and sustainability criteria in order to become competitive.

Climate change is likely to have a significant influence on the types and distribution of biomass grown. Central and northern Europe is expected to see a longer, warmer growing season that will increase the productivity of both bioenergy crops and forests. In other parts of the world, more droughts could reduce productivity and increase the risk of forest fires. Extreme weather can significantly influence the supply of biomass, so we should protect biomass conversion plants by ensuring that they are not dependent on single feedstock.

To help identify the most sustainable agricultural food and energy systems, the EEA developed a catalogue of energy crop species characteristics ranked by their environmental impact (EEA 2006). Table 6 shows the results for selected crops. In general, perennial crops such as clover, alfalfa, reed, canary grass and short-rotation coppice (poplar and willow) have less environmental impact than most annuals.

Table 6

Environmental impact ranking for selected biomass types, as developed by the European Environmental Agency (modified from EEA 2006) The ratings reflect the risk of harm to the environment

	Permanent grass	Clover and alfalfa	Maize	Oilseed rape	Wheat	Sugar beet	Poplar and willow	Red canary grass
Erosion	A	A	C	B	A	C	A	A
Soil compaction	A	B	B	C	A	C	A	A
Nutrient inputs to ground and surface water	A	B	C	C	A	C	A	B
Pesticide pollution	A	A	C	C	B	B	A	A
Water abstraction	A	A	B	–	B	C	B	B
Increased fire risk	B	–	–	–	A	–	–	–
Link to farmland biodiversity	A	B	C	C	C	B	B	B
Diversity of crop types	A	A	C	B	C	B	A	A

A = low, B = medium, C = high

Increasing demand for biomass for bioenergy can create new uses for currently uneconomic outputs from extensive agriculture or forest residues. For instance, grass cut from perennial pastures provides useful biomass, while supporting biodiversity and taking advantage of grassland's ability to lock up carbon in the soil.

New and more tightly integrated cropping systems for food and bioenergy, which may include perennials, could reduce the need for pesticides by increasing biodiversity. Crops such as clover could also reduce subsequent crops' need for artificial fertilisers by its ability to fix atmospheric N_2.

It is important to develop new markets for bioenergy and biomaterials because this will promote a wider range of crops. In turn, this will increase biodiversity and help to create robust agricultural systems that produce high and stable yields of good-quality crops and are resilient to climate change (Østergård et al. 2009).

Aquatic biomass like microalgae and macroalgae could be considered as an alternative future biomass resource. It has barely been investigated so far, compared to terrestrial production, and it is at this stage considered as rather innovative without any major commercial experiences. Nevertheless, aquatic biomass is an interesting resource because it is not increasing the pressure on the already limited land available for biomass production, and at the same time algae has a high biomass production potential and oil content suitable for e.g. biodiesel production. Several options for producing macro-algae are available like harvesting from natural ecosystems, municipal waste and blooms as a result of pollution at sea or in lakes, or open-air or covered ponds with cultivation of either natural algae populations or more purified specific strains. Microalgae will be produced in bioreactor-based systems under optimised conditions, but also with greater capital costs and technical challenges. In any case, a new ecological balance needs to be struck when algae biomass is cultivated and regularly harvested which remains an important research area to be investigated further.

Bioenergy technologies

At present, the most efficient way to convert dry biomass into energy is to burn it in power plants which generate electricity and heating for houses. New thermal technologies which turn biomass into combustible gas may improve the efficiency of this process, particularly when the need to distribute heat dictates the use of a network of small plants. Furthermore, gasification can be used for co-firing "difficult" biomasses in central coal-fired power plants as a substitute for coal. For producing liquid fuel from biomass, gasification combined with catalytic liquefaction is a very efficient route. Biomass containing a large proportion of water cannot be burned directly or gasified using thermal technologies. Instead, effective biological gasification techniques have been developed which allow the conversion of such biomass. Anaerobic digestion of the wet biomass into biogas (methane and carbon dioxide) is a technology that has been used for several decades. Often several wastes are treated together (co-digestion) to ensure stable and high biogas production. The produced biogas can be used for producing heat and power, for fuel in cars or pumped into the natural gas grid. The effluent from the digestion is used as fertilizer. It is very important to understand that biogas production serves several purposes: energy production, agriculture advantages (e.g. improved utilisation of nutrients) and environmental advantages (reduced leaching of nitrate and odour). All these technologies are already in use, and further improvements can be expected.

Electricity generated from biomass can be distributed over long distances and used in a variety of ways. To transport people and goods, electricity can power trains and small battery cars with limited range. Apart from these applications, however, transport is a challenge since efficient, energy-dense and abundant biological substitutes for gasoline and diesel are not available at present.

The liquid biofuels produced today fall into two categories, based on whether they originate from carbohydrates or fats. First-generation bioethanol can be produced from carbohydrates by fermenting sugar cane or maize, in the latter case only after enzymatic depolymerisation of the starch. Low energy density means that bioethanol is not an ideal fuel. At today's oil prices, bioethanol has difficulties competing with gasoline, and reducing the cost of bioethanol is a challenge because the manufacturing process seems to have been nearly optimised. However, in some countries like Brazil a large number of cars run on first-generation bioethanol.

Biorefineries, which produce multiple products from multiple feedstocks, might make bioethanol more economical. However, the biggest problem with bioethanol is the fact that the raw materials from which it is produced are also needed to feed people and animals. Producing enough sugar and maize for all three end-uses, without causing environmental damage, is a big challenge to agriculture.

Fermentable carbohydrates can be obtained from non-food sources like cellulose (straw and wood), but at present the processes for making second-generation bioethanol are very expensive. The challenge here is to develop simple, low-cost production methods.

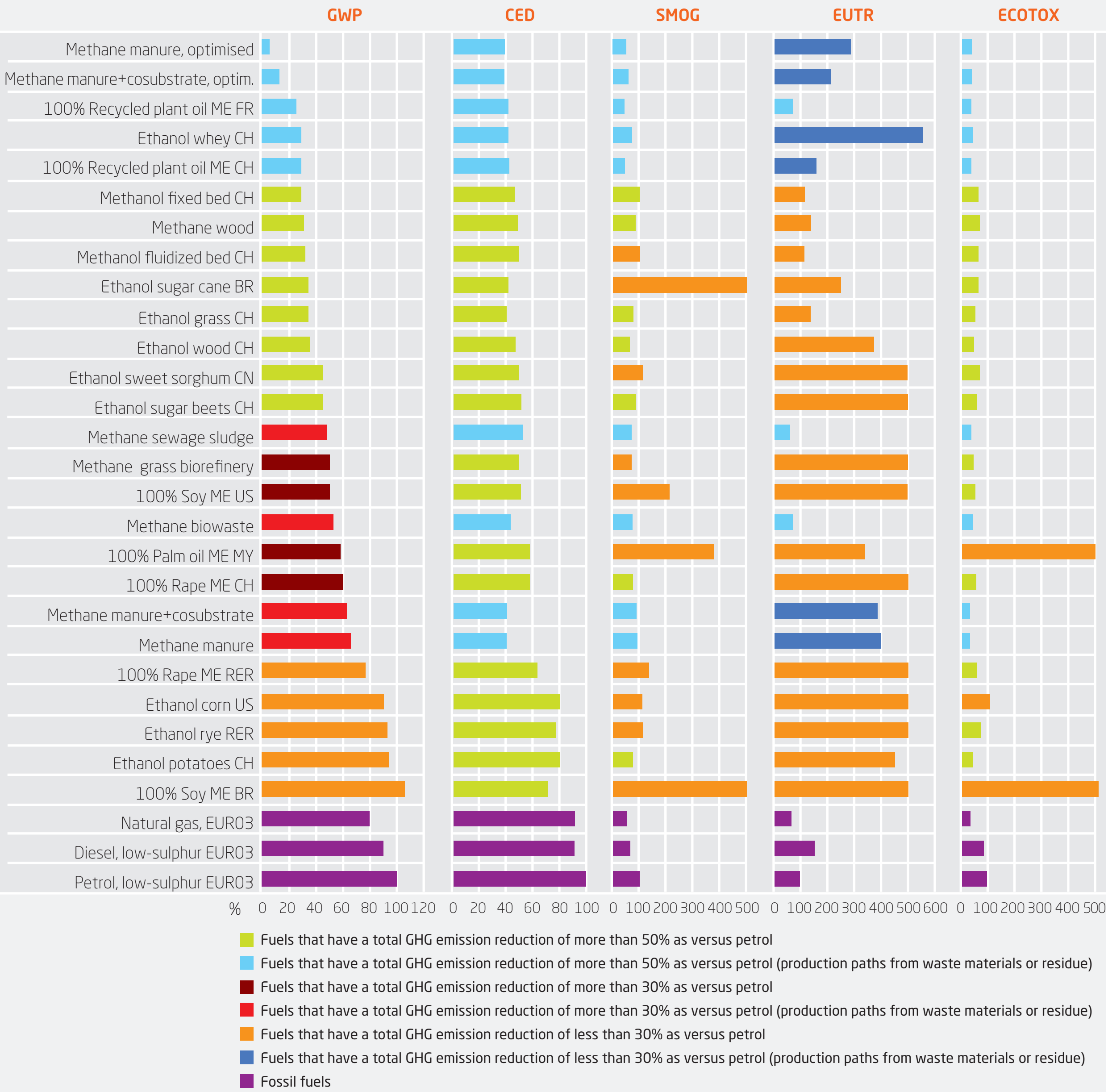
Triglycerides – oils and fats – can be converted into high-quality diesel fuel for combustion engines through technologies and infrastructure that already exist in the chemical industry. The challenge is to produce triglycerides in quantities that are significant compared to the world's huge consumption of transport fuels based on petroleum. At present, biodiesel is made from animal fats and plants with a high oil content, notably rapeseed and palm oil. As with first-generation bioethanol, this production cannot be increased significantly because it competes with food production.

The answer may lie in oil-containing microscopic algae which can be produced in parts of the world, such as deserts, lakes and oceans, that cannot be farmed in a traditional manner.

Microalgae are photosynthetic microorganisms which convert sunlight, water and carbon dioxide into biomass. Their huge photosynthetic capacity makes microalgae much more

Figure 29

Relative global warming potential (GWP) of biofuels. From Zah et al. 2007. Overall environmental Life Cycle Assessment of all unblended biofuels studied in comparison to fossil reference. GWP = greenhouse warming potential, CDE = cumulated non-renewable energy demand, SMOG = summer smog potential, EUTR = excessive fertilizer use, ETOX = ecotoxicity. Reference (=100%) is petrol EURO3 in each case. Biofuels are shown in diagram at left ranked by their respective GHG emission reductions.

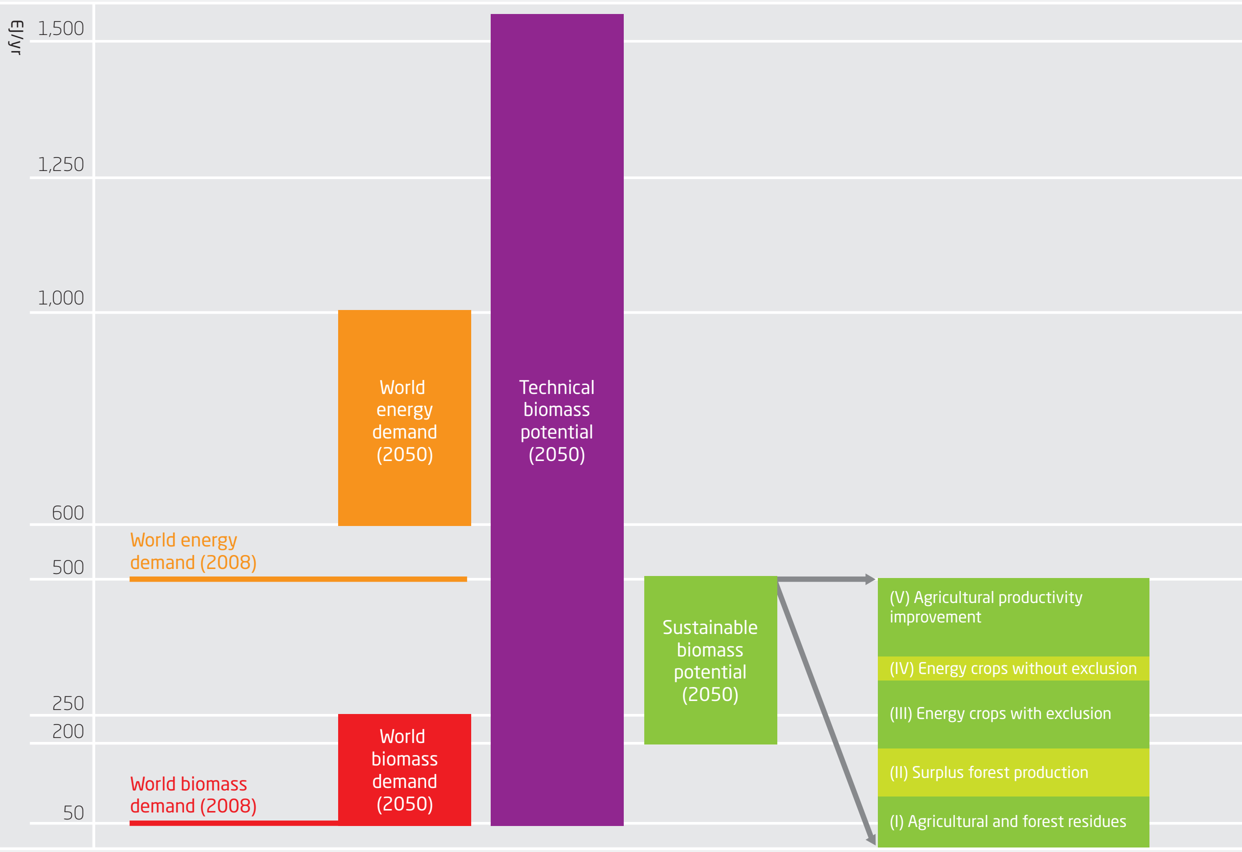


productive than the highest-yielding vegetable oil crops: They out-produce oil palms by a factor of 8-25 and rapeseed by a factor of 40-120 (Christy 2007). Many microalgae are also extremely rich in intracellular lipids (fats), which can reach up to 80% of the dry biomass by weight (Spolaore et al. 2006). Currently, algal biodiesel is still too expensive to be commercialised. The costs of extracting the oil and processing the biodiesel are fairly static, so development needs to concentrate on increasing the biomass production rate and the oil content of the algae.

New knowledge on the cultivation of algae is emerging continuously, and in particular, research on the effects of carbon dioxide concentration and stress has significantly increased productivity in closed reactors. However, only a small part of the potential of microalgae has been explored. As an example, oil production capacity has only been studied for a few species of algae out of the vast numbers available, and then only under conditions which do not fully exploit the physiological diversity of this group of organisms. At Risø we aim to identify previously unrecognised groups of microalgae and adapt them to industrial oil production; important characteristics are growth rate, robustness, symbiotic relationships, extractability and lipid content.

Microalgae can grow in salt water or wastewater. Their ability to remove polluting salts from wastewater, rivers and lakes, when combined with oil production, could yield cheaper

Figure 30
Technical and sustainable biomass supply potentials, expected demand for biomass (primary energy) based on global energy models, and expected total world primary energy demand in 2050. Current world biomass use and primary energy demand are shown for comparative purposes. Source: IEA BIOENERGY 2009



- Current world energy demand (500 EJ/yr)
- Current world biomass demand (50 EJ/yr)
- Total world primary energy demand in 2050 in World Energy Assessment (600 - 1000 EJ/yr).
- Modelled biomass demand in 2050 as found in literature studies (50 - 250 EJ/yr).
- Technical potential for biomass production in 2050 as found in literature studies (50 - 250 EJ/yr).
- Sustainable biomass potential in 2050 (200 - 500 EJ/yr). Sustainable biomass potentials consist of:
(I) residues from agriculture and forestry (~ 100 EJ);
(II) surplus forest production - net annual increment minus current harvest (~ 80 EJ);
(III) energy crops, excluding areas with moderately degraded soils and/or moderate water scarcity (~ 120 EJ);
(IV) additional energy crops grown in areas with moderately degraded soils and/or moderate water scarcity (~ 70 EJ) and
(V) additional potential when agricultural productivity increases faster than historic trends thereby producing more food from the same land area (~ 140 EJ).

biofuels. Another example of a double benefit would be to use microalgae to consume carbon dioxide removed from power station flue gas.

After the oil has been extracted, the residual algal biomass contains substantial amounts of protein with an amino acid composition that makes it suitable as an animal feed or even as food for humans. Such an application fits the idea of a biorefinery producing both fuel and food.

Sustainability

In the context of bioenergy, an important issue is the potential of biofuels to mitigate global warming by reducing emissions of greenhouse gases (GHGs), most importantly carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Other air pollutants relevant to global warming are soot, aerosol particles, nitric oxide (NO), carbon monoxide (CO) and ozone (O_3); the last of these, as well as being a GHG, is bad for human and plant health.

Assessments of sustainability should take account of the energy used to produce, handle and process the feedstock, any changes in land use needed to grow fuel crops, and the effects on food production and prices. Sustainability analysis is quite complicated, and it is often difficult to compare different analyses. Work has therefore started to define a common set of criteria by which to measure the sustainability of biofuels (European Commission 2010).

As Figure 28 shows, a wide variety of feedstocks can be used for biofuels. Figure 29 provides an overview of the global warming potential (GWP) of various biofuels relative to petrol (gasoline); note that there is some controversy about the exact numbers, depending on how the analysis is done.

According to this study, biogas from manure provides the lowest GWP, provided that none of the CH_4 produced is lost at a later stage. Lignocellulosic (second-generation) bioethanol is also attractive, with a GWP of typically 50-80% below that of fossil fuels. Corn ethanol and biodiesel from rapeseed oil have much greater GWPs, often only about 20% below that of petrol. However, this analysis for biodiesel includes only the rape seeds; using the whole plant can significantly improve the sustainability of oilseed plants in energy production. Another benefit of bioethanol is that when used in petrol at concentrations as low as 6%, it avoids the need to add the toxic chemical MBTE, which is used to increase the octane number.

As Figure 29 shows for soybeans, biofuels can actually have worse GWPs than fossil fuels if we take into account changes in land use (Searchinger et al. 2008). A recent study concluded that the best solutions for light transport were wind-powered battery-electric or hydrogen fuel cell vehicles (Jacobson 2009). The worst solutions were shown to be biofuels from corn and lignocellulosic ethanol, which could even worsen climate change and air pollution; despite their relatively low GWPs, these fuels bring other environmental concerns.

We should therefore consider biofuels carefully in terms of the energy balances, GHG savings and potential secondary pollution associated with their feedstocks and manufacturing processes. To ensure that future biofuels are sustainable, the EU has set up rules for certification (EU 2009).

Future share of bioenergy

It is difficult to assess the possible contribution of bioenergy to future energy demand. Many attempts have been made to do this, some optimistic and others pessimistic. One of the more balanced approaches is that of the International Energy Agency (IEA Bioenergy 2009). The IEA report distinguishes between the technical potential, which is the unconstrained production potential limited only by the technology used and the natural circumstances, and the sustainable potential, which further considers a range of environmental and social constraints in order to guarantee sustainable feedstock production.

According to the IEA estimate, the total sustainable biomass potential in 2050 is 200-500 EJ/yr out of a total world primary energy demand of 600-1,000 EJ/yr. Thus by 2050 biomass has the potential to meet a substantial share – between a quarter and a third – of the world's energy demand (Figure 30).

Conclusions

Bioenergy will certainly play a larger role in future, both in Denmark and globally.

A large proportion of biofuel use will probably still be as wood and agricultural waste for direct burning in less developed areas of the world.

Biomass has special roles to play as an easily storable form of energy, as a fuel for CHP based on sophisticated combustion technologies, and as a source of liquid fuel for transport.

Much more organic waste can be used for bioenergy, solving a waste problem and recirculating nutrients to ecosystems. New biomass forms such as algae can also contribute. Several techniques are now being developed with a view to improving biomass use, and this rise in productivity will help to make biofuels competitive when oil prices increase.

It is not likely, however, that bioenergy will be able to provide the bulk of the world's energy, but it can make a substantial contribution. Biomass is a limited resource, and it is a challenge to increase biomass production in ways that do not compete with our food supply and have no negative environmental impacts.

9
Geothermal energy

Jørgen Fenhann, Risø DTU, Denmark; Anders Mathiesen and Lars Henrik Nielsen, The Geological Survey of Denmark and Greenland (GEUS), Denmark

Heat from the interior of the Earth is transmitted through the Earth's continental crust at a rate corresponding to a temperature gradient of normally 25-30°C per kilometre. The main sources of this energy are due to heat flow from the Earth's core and mantle and that are generated from the nuclear decay of natural radioactive isotopes (238U, 235U, 232Th and 40K). In general terms, geothermal energy is divided into the following systems.

Low temperature

Heat production from porous sandstone layers, typically 800-3,000 metres below ground. From these reservoirs, it is possible to exploit water with temperatures of 25-90°C. The geothermal system consists of one or more production wells, heat exchangers and/or heat pumps transferring heat into the district heating network and one or more re-injection wells returning the cooled water to the same reservoir maintaining the reservoir pressure. The heat pumps can either be compressor heat pumps driven by electricity or absorption pumps driven by heat. The assessment of when it is economically and environmentally ideal to use electrical heat pumps or absorption heat pumps depends on the energy source used to generate the electricity.

Middle and high temperature

Geothermal heat at a temperature level where generation of both heat and power is possible. The high temperatures are often found in connection with volcanic activity.

Geothermal energy can be used for electricity generation, but the temperatures in the Danish subsurface are, with the present technology, not sufficiently high to produce electricity directly. At least 24 countries produce electricity from geothermal energy, and 76 countries use geothermal energy for heating and cooling without conversion.

In 2008, the worldwide production of geothermal heat was 186 PJ/yr (ENERDATA 2010), up 43% from 1999 to 2004. Global geothermal electricity production capacity increased from 8,933 MW in 2005 to 10,715 MW in 2010, representing an increase of 20% (Holm et al. 2010), see the top 10 in Table 7. The top 10 countries in geothermal electricity production (Holm et al. 2010) and in geothermal heat use (ENERDATA 2010).

Table 7 shows that many of the top countries generating electricity from geothermal resources are developing countries. The USA is presently the top geothermal electricity producer. The State Renewable Portfolio Standards and the Federal Production Tax Credit have opened a market opportunity for geothermal power. The activity is concentrated in a few western states, particularly in California and Nevada.

Outside the USA, more than 30% of the global capacity is installed in the Philippines and Indonesia. Indonesia is expected to evolve as the larger geothermal growth market in the longer term due to its resource potential (Stephure 2009).

The countries in Central America can serve as an example of the development potential that exists in densely populated geographical regions. El Salvador, Costa Rica and Nicaragua are among the six countries where geothermal power supplies more than 10% of the national electricity. It has been estimated that the geothermal potential for electricity generation in Central America is 4,000 MWe (Lippman 2002), and only about 500 MWe of this potential has been harnessed so far.

In Europe, high temperatures at shallow depth are found in Italy, Turkey and in Iceland, as well as in other oceanic islands such as the Azores. The installed generating capacity in the EU has grown from 370 MW in 1970 to 893 MW in

Table 7
The top 10 countries in geothermal electricity production (source: Holm et al. 2010) and geothermal heat use (source: ENERDATA 2010)

Geothermal electricity production		Geothermal heat production	
2010	MW	2008	PJ/y
USA	3,086	Turkey	45.8
Philippines	1,904	USA	44.3
Indonesia	1,197	Iceland	28.4
Mexico	958	New Zealand	19.7
Italy	843	Italy	8.9
New Zealand	628	Japan	8.8
Iceland	575	France	4.8
Japan	536	Hungary	3.6
El Salvador	204	Georgia	0.7
Kenya	167	Denmark	0.5
Total	**10,098**	**Total**	**165.4**

2005. Most of the capacity is installed in Italy and Iceland. The 10 MW of capacity installed in Portugal is located in the Azores, where capacity will soon be doubled.

Hot dry rock geothermal energy

Hot dry rock formations at a depth of 3,000-4,000 metres or more below ground are another source of geothermal energy. The technology for utilising the energy is still being developed, as described in the next section.

1.1 New developments

In the past two decades, there have been several projects involving heat mining by injecting cold water into hot rocks in deep boreholes. These heat mining projects have operated under different names, such as "Hot Dry Rocks (HDR)", "Enhanced Geothermal Systems (EGS)" and "Engineered Geothermal Systems (EGS)", and have been tested to various extents in the USA, Europe and Japan.

At a depth of 5,000 metres, temperatures are around 200°C in an area covering 125,000 square kilometres under Europe. The "European Hot Dry Rock" project within the 6th EU Research Framework utilises widened natural fracture systems and injects water at high pressure that is then heated and returned to the Earth's surface via several production wells. Europe is currently the leader in this technology. A 1.5 MW pilot plant has been built in Soultz-sous-Forêt (Soultz 2009), and a small commercial plant exists in Landau, Germany. A high-temperature source is also available under Denmark. The achievement of the Soultz experiment and several other successful spin-off projects open the adult age for the development of EGS. A real boom can be observed in Australia, where large volumes of geothermal heat have been located at a depth of up to 4.5-5 kilometres. More than 50 companies are exploring geothermal energy projects in Australia (The Economist 2010). The first EGS plants will be built in Australia in 2010 (Bertani 2007). Over the next 10 years, Geodynamics, a company based in Queensland, Australia, is planning to build ten 50 MW power plants by drilling 90 wells in the Cooper Basin, a desert region in South Australia with large geothermal energy reserves.

A comprehensive assessment of enhanced geothermal systems was carried out at MIT to evaluate the potential of geothermal energy in the USA. Despite its enormous potential, the geothermal option for the USA has been largely ignored. The conclusion of the study was that, if just 2% of the thermal energy available in the rocks 3-10 kilometres beneath the Earth's surface could be tapped by EGS, it would be more than is needed to supply all of America (MIT 2007). For it to be tapped, however, both technical and economic hurdles must be overcome.

A new acronym has recently been added: DUGR for Deep Unconventional Geothermal Resources. DUGRs require drilling to depths of 4-5 kilometres with temperatures in the 400-600°C and high-pressure range and can produce supercritical fluids since the critical point for water is 221 bars and 374°C. If DUGR is possible, the global geothermal potential could increase by a substantial factor. The concept is to bring the supercritical fluid to the surface where it transitions directly to superheated steam, resulting in a ten times bigger power output from a well. The first such drilling started in 2008 in the Iceland Deep Drilling Project (IDDP). Geothermal reservoirs at supercritical conditions are potentially to be found worldwide in any active volcanic complex.

1.2 Geothermal heat in Denmark

Two Danish geothermal plants, the Thisted plant in northern Jutland and the Margretheholm demonstration plant near Copenhagen (Figure 31), have shown that it is possible to produce large volumes of warm water for district heating. Only 5-10% of the total energy output from the plant is used to extract the heat from the subsurface by pumping warm formation water to the surface and returning it to the subsurface in a closed system. Both Danish plants have two wells, a production well and an injection well in which the cooled formation water is returned to the geological reservoir about one kilometre away from the production point, in order to avoid mixing warm and cold water.

In the past five years, the utilisation of geothermal energy has attracted growing interest. This is further substantiated by ongoing studies around Sønderborg and Viborg, where it is expected that new geothermal plants will be established within the next few years. Furthermore, several local district heating plants are currently looking into the possibilities. It is estimated that 32 existing district heating networks have a potential for utilising geothermal heat (Danish Energy Agency 2010).

Because geothermal energy is expected to play an increasingly important role in Denmark's energy strategy, the Geological Survey of Denmark and Greenland (GEUS) and the Danish Energy Agency have conducted a regional study to update the assessment of the geothermal potential in Denmark (Mathiesen et al. 2009). Based on existing well, seismic and temperature data and the detailed knowledge of the subsurface stratigraphy gathered by GEUS over many years, the assessment has documented a huge geothermal potential in many parts of Denmark, even though the specific potential in local areas was not evaluated in detail.

Four main stratigraphic units with a regional geothermal potential have been identified, and are generally described as five geothermal reservoirs defined by their stratigraphic and area extent and each containing a large number of potential sandstone layers. The new assessment shows that large areas have a large geothermal potential, as they contain several porous and water-bearing sandstone reservoirs in the economic interval 800-3,000 metres below ground with formation temperatures of 25-90°C (Mathiesen et al. 2009). It is estimated that the geothermal resource in Denmark amounts to several hundred years of the present heat consumption, and only a small fraction of this potential is utilised by the geothermal power plants in Thisted and Margretheholm.

A major challenge in geothermal prospecting is finding suitable reservoirs with high continuity (small number of faults and lateral changes in lithological composition) and sufficient flow capacity (thickness, porosity and permeability) of warm water. The new assessment (Mathiesen et al. 2009) stresses that depositional processes during the formation of the reservoirs and their subsequent burial depths determine their qualities as geothermal reservoirs. The reservoir quality is primarily described by porosity and permeability, factors that decrease with increasing depth due to mechanical compaction and the formation of diagenetic minerals which both reduce pore volume (porosity) and the connections between the pores (permeability).

However, the mutual dependency of the various factors and processes is not fully understood, which weakens the predictive strength and reliability of the geological models currently used to identify areas of interest. Permeability is very critical, but difficult to predict since very large variations occur depending on depositional facies, provenance, mineralogical composition, burial history and position in the basin.

One of the barriers to a significant increase in the exploitation of the large geothermal resource in Denmark is the geological uncertainty in the exploration phase. This uncertainty relates to the extent to which it is possible to make accurate and reliable predictions of the presence in the subsurface of sufficiently high-quality reservoirs with high lateral continuity below urban areas where the infrastructures and consumers are in place. Precise predictions are dependent not only on existing well and seismic data, which show a highly variable density and quality, but also on our understanding of the geological processes that lead to the formation of the geothermal reservoirs.

A newly funded multi-disciplinary research project headed by GEUS will address these uncertainties.

The potential for using geothermal energy from aquifers in the Danish subsurface is very large because it is highly suitable for district heating systems. It is expected to cover a large part of the demand for district heating in the future. The partners in the Greater Copenhagen geothermal licence have completed a study on the geothermal reserves in the area. The conclusion was that the producible heat at a commercial cut-off heat price in the Greater Copenhagen area reaches 60 EJ/yr. Compared to the district heat consumption for the area of 40 PJ/yr, the underground is seen to have a capacity to supply whatever heat is needed for thousands of years (Magtengaard 2010). Heat storage in combination with the utilisation of geothermal energy is at an early stage.

Figure 31
Potential sandstone reservoirs in Denmark at depths of 800-3,000 m and with thicknesses above 25 m

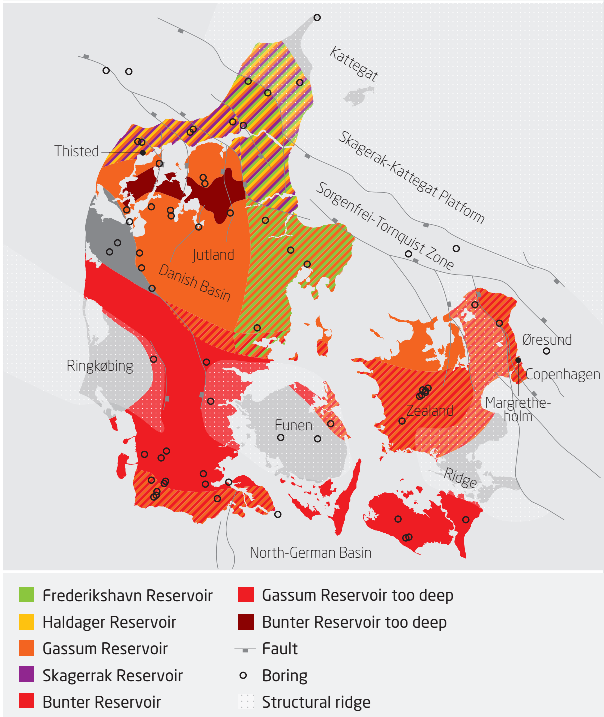


Figure 31 The distribution of potential sandstone reservoirs in Denmark with depths in the 800-3,000-metre interval and thicknesses above 25 metres. The dark-grey and dark-brown areas indicate that the reservoirs are buried too deep (Gassum in northern Jutland, Bunter in western Jutland; both located in the central parts of the Danish Basin), while the light-grey areas indicate areas where no reservoirs are expected to be present (Ringkøbing-Funen High) or the reservoirs are too shallow (< ~800 m; northernmost Jutland). The hatched areas indicate that two or more of the mapped reservoirs are expected to have geothermal potential. The existing deep wells are shown together with the location of the two geothermal plants at Thisted and Margretheholm near Copenhagen.

In future, waste heat from, for example, solar plants and incineration plants could be used for heating the geothermal reservoir temperature in summer. In winter, it would then be possible to increase the energy output from the reservoir.

Conclusions

The present annual global consumption of primary energy is about 500 EJ. AR4 estimated the global potential at 50 EJ/yr, which is now considered conservative. Table 4.3 in AR4 estimated the geothermal energy resource available (including potential reserves) at 5,000 EJ/yr. The International Energy Agency has estimated the most probable potential for the global geothermal resource at 205 EJ/yr (Danish Energy Agency 2010), including 65 EJ/yr from electricity production.

An analysis by Goldstein et al. (2008) yields a forecast for global EGS deployment of 10% of the global baseload power by 2050 without considering commercial risks or technical uncertainties.

The beauty of the EGS concept is that it can work almost anywhere in the world. The International Geothermal Association predicts that there will be 160 GW of geothermal electric capacity installed worldwide by 2050, about half of which will be EGS. Whether EGS can overcome the obstacles it currently faces should become clear in the next decade. The company Geodynamics imagines that, in a couple of decades, all the drilling rigs which will be redundant because we have run out of oil will be drilling geothermal wells instead (The Economist 2010).

10
Energy storage

Allan Schrøder Pedersen, Risø DTU, Denmark; Robert Remick, NREL, USA; Claus Krog Ekman, Danish Energy Agency, Denmark

The need to store energy

The production of renewable energy is to a large extent variable and difficult to control. In contrast to fossil energy, renewable energy must therefore be harvested when it is available, and to maintain a balance between production and consumption, some sort of energy storage is needed or at least of value. This is true of energy used in the power sector, for transport fuels, and of the various thermal sources used to heat and cool buildings.

At present, the balance between consumption and production is relatively easy to maintain, since most of the energy we consume is stored in fossil fuels which can be readily used when needed. However, as the penetration of renewable energy increases, balancing production and consumption will become more challenging.

The challenges depend largely on the mix of renewable energy sources in the different sectors and the strength of the links between the sectors. For example, bioenergy from renewable sources can be transformed into liquid biofuels and biogas, so its consumption in, say, the transport sector does not pose any challenges different from those associated with fossil fuels. For that reason, we will not consider energy storage in the form of biomass and biofuels any further in this chapter.

Instead, we focus on energy storage technologies and their possible uses in a renewable energy system. The biggest challenges are in the electricity sector, where the real-time balance between production and consumption is closely linked to grid stability. However, energy storage technology can also facilitate higher levels of renewable energy in the heating, cooling and transport sectors.

This chapter contains sections covering thermal energy storage, electrical energy storage for stationary applications and energy storage for transport. The focus is on applications and technologies with the potential to facilitate the transition to a fossil-free energy system.

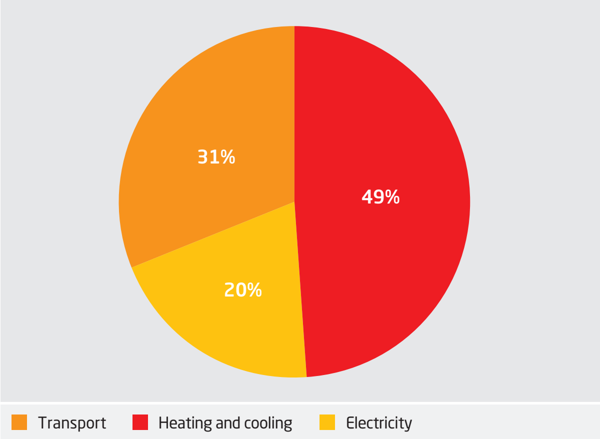
Thermal energy storage

Heating and cooling account for almost half of the total final energy demand in industrialised countries (Figure 32).

Heat for buildings and industrial processes today comes primarily from electricity and the combustion of fossil fuels, either just for that purpose or in combined heat and power plants. Cooling is done by electric heat pumps, the electricity often coming originally from fossil fuels.

In a future renewable energy system, heating can come from a number of sources, including geothermal energy, the combustion of renewable fuels, from combined heat and power systems (including nuclear plants), electric heat pumps, solar thermal collectors and electric heaters. In future, cooling will mainly be provided by electric heat pumps.

Figure 32
Distribution of final energy demand in the EU in 2006. Source: European Solar Thermal Technology Platform [10]



Since heat demand does not necessarily follow power demand, the balance of production and consumption from combined heat and power plants is sometimes challenged. Furthermore, direct heat sources such as solar heating are typically less available when the heat is actually needed than when it is not. Cooling and heating demands are also not well correlated with renewable power production, and this challenges the use of fluctuating renewable sources to power the necessary heat pumps.

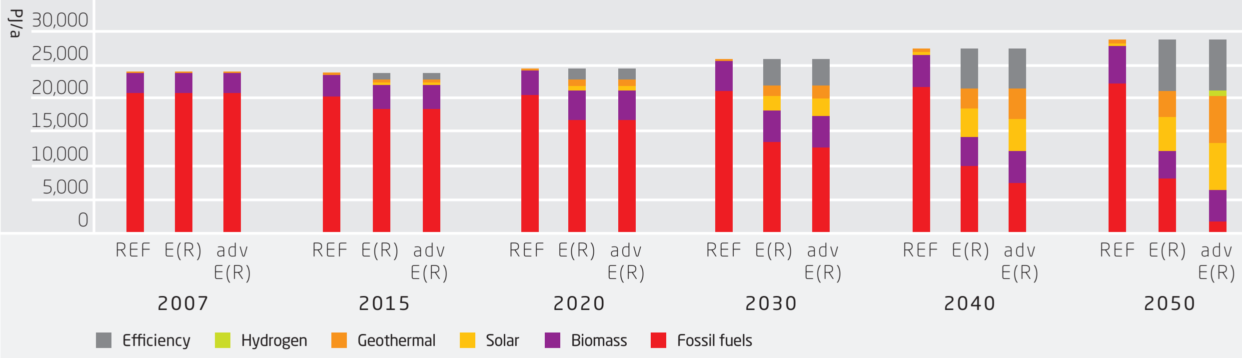
The challenges can be overcome effectively by adding heat and cold stores. These add valuable flexibility to energy systems, not only for heating and cooling but also in their links to electricity production.

Based on scenarios cited in Figure 33, efficiency gains in heating could save about 3,000 PJ/yr by 2050 in the OECD Europe countries, representing 10% of total heat demand. This would be achieved through better energy management in buildings and industrial processes, but not simply through thicker insulation or improved design of industrial processes; about a third of the energy saving would depend on the appropriate use of heat storage.

Thermal energy storage technologies fall into two categories based on the physical processes involved: phase change materials (PCM) and sensible heat storage.

PCMs take advantage of latent heat – the large amounts of heat released or absorbed when materials change phase be-

Figure 33
Development of the heat supply structure under three scenarios for OECD Europe. The two non-reference scenarios show savings of about 10% by 2050 relative to 2003. Such savings rely on considerable efficiency improvements, which will in turn require extended use of energy storage



tween solid and liquid, or liquid and vapour. The fact that PCMs absorb and release heat at a constant temperature is an advantage in heat storage applications.

PCMs can have energy densities to the order of 100 kWh/m^3, and are commercially available with operating temperatures from –21°C up to 120°C. Reference 2 contains an extensive list of PCMs and their applications.

Heat stored or released by changing the temperature of a storage medium is known as sensible heat because the temperature change can be felt (latent heat, in contrast, is "hidden" because it involves no temperature change). The most common application of sensible heat storage is in district and domestic heating and is based on water, which is cheap and safe. Water also has a high heat capacity: The energy stored by heating a cubic metre of water from 20°C to 95°C is about 90 kWh.

Heat storage in large water tanks is commonly used in combined heat and power plants supplying district heating. An example is the system at the Avedøreværket coal-fired power plant in Copenhagen, which stores about 2.6 GWh [3]. Water-based heat storage is also used with solar heat collectors, collecting heat during the summer and releasing it for domestic heating during the winter [1].

A characteristic of thermal energy storage is that larger systems are more efficient. This is because doubling the dimensions of the tank increases the heat storage capacity eightfold, but the area from which heat is lost increases only fourfold. Very large systems (like underground caverns or aquifers) are therefore a relatively efficient way of storing large amounts of energy (possibly for heating or cooling in urban areas) in the future energy system. Such large energy storage systems could function as energy buffers on a seasonal basis, allowing higher penetrations of fluctuating power sources like wind and solar power.

Electrical energy storage for stationary applications

Integrating more renewable, intermittent energy, like wind and solar power, into the electrical grid brings two challenges which could in principle be addressed through electricity storage. Both relate to the fluctuating and unpredictable nature of renewable power sources, but on different timescales.

Fluctuations in renewable power production require the remaining generating units to be very flexible. The first challenge is therefore what to do if fluctuating renewable power sources are to completely replace fossil-fuelled power plants; without electricity storage, security of supply will be compromised when renewable power is not available, for instance at times with no wind. Large electricity storage systems can help by absorbing excess renewable energy during hours or days of high production and low consumption, and then releasing it when production is low and demand is high.

The second challenge is that the variable nature of renewable energy generation makes it more difficult to plan power production, and this in turn increases the need for short-term regulation and reserves. This issue can be overcome by adding electricity storage systems that can provide both up and down-regulation as well as reserves at short notice, sometimes down to below one second.

One interesting technology for short-term regulation is mechanical flywheels. These have made considerable technical progress in recent years thanks to companies such as Beacon Power in the USA (Figure 34). Working at timescales of seconds to minutes (between inertial reserve and spinning reserve), they combine high regulating effectiveness with almost instantaneous response.

Many other stationary electricity storage technologies have been developed, and several systems are operating around the world, although not in widespread use. In addition to flywheels, other well-known technologies are stationary batteries (typically used for fast response), compressed air energy storage (CAES) and pumped hydro, both of which are suitable for spot market arbitrage.

Figure 35 provides an overview of electricity storage technologies in terms of rated power and discharge time (energy capacity). The graph was prepared by the Electricity Storage Association (www.electricitystorage.org) in 2008, but is still an excellent guide to the general suitability of the various technologies for different applications.

It is the opinion of the authors that storage systems are likely to increase their market in the near future, while new technologies currently being developed will reach commercial maturity in the next few decades. An example of a system which might be seen by 2050 is the "energy island" (Figure 36). The underlying technology is simply pumped hydro, but unlike pumped hydropower, the energy island does not require mountains – though there are other problems to be overcome. It illustrates the kind of vision we need to overcome the challenges posed by the widespread use of sustainable energy.

Figure 34: 100 kW/25 kWh Beacon flywheel unit. The flywheel is sealed in a vacuum chamber and spins at 8,000-16,000 rpm (source: Beacon Power, www.beaconpower.com)

Figure 35

System ratings for electricity storage technologies. Source: Electricity Storage Association, www.electricitystorage.org/ESA/home

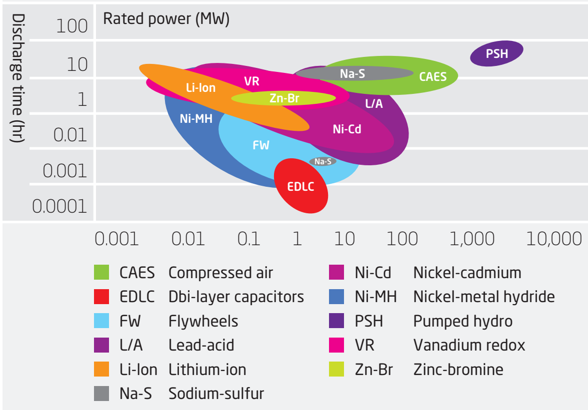


Figure 36: Artist's impression of an energy island. At the centre is a deep reservoir from which water is pumped out when electricity is plentiful. The electricity is later regenerated by turbines through which water flows back into the reservoir. The concept could be expanded with solar cells (circle in the middle) and algae production (source: Gottlieb Paludan Architects)

Energy storage for transport

The transport sector accounts for approximately 20% of the world's total energy demand (30% in many developed countries like Denmark) and is powered almost exclusively by fossil fuels. There is little doubt that this picture will change as we move towards 2050: Renewable sources will have to take over for environmental reasons and due to a decline in fossil fuel resources.

The energy currently used for transport is mostly stored on board vehicles in tanks containing liquid fossil fuels, exceptions being electric trains and buses supplied directly from the grid. A shift to sustainable energy in the form of electricity (i.e. bioenergy disregarded) will require mobile technologies which can store electricity from wind and solar sources in concentrated form, guaranteeing driving ranges similar to those of gasoline and diesel vehicles. Range is especially important for drivers of private cars, who appreciate the freedom their vehicles provide and are likely to demand the same capability from future electric vehicles.

Batteries may at a first glance seem the obvious way of storing electrical energy for transport. Unfortunately, the driving ranges guaranteed by even advanced batteries fall far below those possible with fossil fuels. The fundamental problem is that the energy density of batteries is almost two orders of magnitude lower than that of fossil fuels. This means that about 1.5-2 tonnes of batteries are required to provide the same driving range as a tank holding 50 kg of gasoline, even taking the different conversion efficiencies into account.

Since such a great weight of batteries is clearly not viable, the idea of combining batteries with other fuel systems (sometimes called range extenders) is attracting interest among car manufacturers. The parallel fuel system could be hydrogen or another synthetic fuel made using wind or solar power. At some point in the future, it may even become economical to use synthetic hydrocarbons made from hydrogen and carbon dioxide extracted from the atmosphere. The technologies required to do this are complicated but well-known.

It is worth noting that consumers may value the convenience of liquid fuels over future energy storage methods that are more direct and more efficient, even if they end up paying more as a result. Today's liquid-fuelled vehicles have driving ranges of around 1,000 kilometres. The distribution system for liquid fuels is already in place, so new synthetic liquid fuels would not need huge investments in infrastructure. Engines for liquid fuels are highly developed and affordable, so there may be no need to rush new traction systems such as fuel cells and batteries to market before they are fully developed. Finally, synthetic liquid fuels are easily blended with biofuels.

Nevertheless, batteries will undoubtedly see dramatic changes in the coming decades. The trend towards new battery types with higher power outputs and greater energy densities is already noticeable. By 2050, rechargeable lithium-air batteries with properties much better than those of current batteries are likely to be on the market, since intense development is going on in many countries.

We anticipate that electricity storage for transport applications will become embedded in future electricity grids and markets. Depending on the market, producing synthetic transport fuels and charging transport batteries may become the preferred use for surplus electricity. In this way, transport-related energy storage may come to play the same balancing role in the power system as we discussed above under electrical energy storage for stationary applications.

The logical conclusion is to devolve control for exchanging energy with vehicle batteries or generating synthetic fuels to the companies which control the transmission grid, and are therefore responsible for balancing electricity supply against demand. This fits in with the concept of a future intelligent energy system, where the supply and demand of electricity are both controlled and optimised according to needs as well as prices.

Conclusions

The vision of fossil-free energy by 2050 is not unrealistic, provided we are determined to make it happen and perhaps willing to pay a little extra, at least for a while. Fossil fuel resources are certain to run out eventually, and before this happens we can expect fossil energy prices to increase dramatically. As fossil energy becomes more expensive, sustainable energy will become competitive.

A fossil-free future will require energy storage, but to what extent is difficult to judge. So far, electricity storage has received much R&D attention, probably because it has the most obvious, straightforward and urgent role to play in the energy market.

However, Figures 32 and 33 above also show that heat storage has considerable technical and economical potential. Unfortunately, heat and cold storage is currently not very efficient, especially over long storage periods, because it depends on thermal insulation. In future, huge underground thermal storage reservoirs may be used for seasonal storage of heat and cold wherever there is an appropriate balance of local climate and geology. If these reservoirs are large enough, their energy losses could be relatively small.

The technical potential for energy storage is enormous, but unfortunately the costs are often considerable and sometimes prohibitive. New ideas and technologies which could lower energy storage costs should therefore be encouraged.

Some emerging technologies could also reduce the need for storage. Examples are smart management of electricity demand and transmission of electricity over very long distances, perhaps using superconductors, so that we could move electricity economically from a region with surplus wind power, for instance, to one where the wind is not blowing. However, this would not solve the problem of mobile energy storage for transport.

We have no doubt that many types of electricity storage will be important in the coming decades as components of the future integrated and sustainable energy system.

11
Nuclear energy

Jens Juul Rasmussen, Bent Lauritzen, Lars Martiny and Erik Nonbøl, Risø DTU, Denmark; Ian Hutchinson, MIT, USA; Hartmut Zohm, Max Planck Institute for Plasma Physics, Germany

The energy released in nuclear reactions is orders of magnitude greater than the molecular energies released in the breaking and forming of chemical bonds. As a result, the stored energy density in nuclear fuel is about one million times larger than in fossil fuels.

This fact is exploited in nuclear power reactors. A 1 GWe power plant uses roughly one train car of uranium per year, whereas a coal plant of similar size needs about one long train load of coal per day. With fusion reactor technology, the hydrogen contained in a bathtub of water and the amount of lithium in a single battery would in principle provide all the energy needed for one person's lifetime.

Nuclear **fission** is a proven technology, but for the past 30 years its exploitation has grown only slowly. However, the need to cut reliance on fossil fuels and reduce greenhouse gas emissions has led to renewed interest in nuclear energy, and many countries now plan to introduce or expand nuclear fission power.

As the amount of fuel needed for nuclear fission is very small, the volume of waste is correspondingly small. However, nuclear reactions produce radioactive elements, so this waste must be sequestered to prevent danger to the public. In addition, exploitation of nuclear fission energy is closely linked to the potential proliferation of nuclear weapons. To accept nuclear expansion, the public needs assurance that these risks are being controlled effectively.

Nuclear **fusion** power is a developing technology which will most likely not be available for large-scale electricity production until the middle of the century. The successful development of fusion energy, however, would make the exploitation of nuclear energy even cleaner, with less radioactive waste. Since nuclear fusion does not involve fissionable materials, the anti-proliferation challenge will be considerably smaller than with fission power.

Fission energy – current status and outlook

Nuclear fission splits heavy elements, in particular uranium, releasing energy and neutrons. The neutrons allow the fission process to be sustained through a controlled chain reaction in a nuclear reactor.

Nuclear fission reactors are deployed in 30 countries, predominantly OECD members in North America, Europe, south-east Asia and the former Soviet Union. Nuclear fission provides 14% of the world's electricity, though this figure has fallen slightly in recent years.

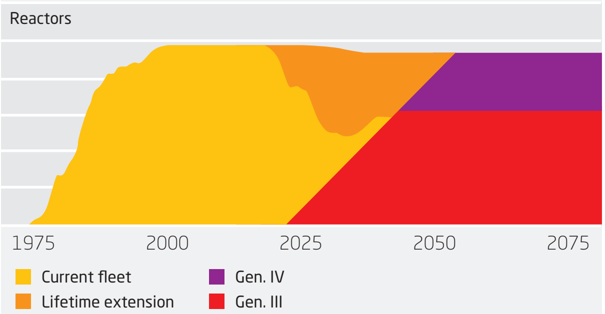
Most nuclear power reactors operating today are light-water reactors built in the 1970s and 1980s. Heavy-water reactors were developed in Canada and India, while the UK focused on gas-cooled reactors. The less safe RBMK-type power reactor was developed in the Soviet Union, but has since been abandoned outside Russia. Russia and Japan each have one operating fast-breeder power reactor.

Reactor sizes range from very small first-generation prototypes up to the large third-generation reactors (1,700 MWe) currently being built in Finland and France. As nuclear plants are expensive to build but rather cheap to run, thanks to their low fuel consumption, nuclear energy is used mainly for base-load electricity production. Other uses of nuclear energy are limited but include ship propulsion and district heating.

In the mid-1980s, the building of new nuclear reactors in the USA and Europe almost came to a complete stop. This was mainly caused by construction-cost overruns and the poor reliability of nuclear power plants in the USA, as well as the accidents at Three Mile Island in 1979 and at Chernobyl in 1986. The performance and safety of nuclear reactors, however, continued to improve. Capacity factors are now up to 90%, yielding nuclear power that is more economical and reliable than ever before.

The European Union aims to maintain European competitiveness in fission technologies, and the development of so-called Generation IV reactors is a priority for the EU (Figure 37) [1]. It is left to individual member states, however, to decide whether and how to use nuclear energy. France, the UK, Finland, Poland and a number of countries in eastern Europe are planning to build new nuclear plants, while Germany, Spain and Belgium currently have policies calling for a phase-out of nuclear power. Sweden's phase-out has been halted, and the present government has removed the ban on planning and building new reactors. The USA expects a nuclear renaissance, with licence applications for 28 new reactors under consideration by the regulators. China, India and

Figure 37
Future deployment of Generation III and IV reactors. Source: EDF, ENC, 2008



Russia have even more ambitious plans to expand nuclear power, installing 100, 60 and 20 GWe, respectively, by 2030.

Based on existing plans, world nuclear capacity may therefore increase from the present 340 GWe to more than 1,000 GWe in 2050, enabling nuclear power to provide 20% of all electricity [2].

Most of these new reactors will be of Generations III/III+. Most existing Generation II reactors are expected to have their operating lives extended to 60 years, helping to bridge the gap until sufficient new capacity can be installed. Generation IV technology awaits further development and probably will not become an option for commercial power production until after 2040.

Whether these expansion plans materialise depends on a number of factors, including public acceptance, financing and how well the new Generation III+ reactors being built today will perform. Another important factor is the availability of skilled personnel and the specialised manufacturing infrastructure needed to install and run the plants.

Because nuclear plants do not produce carbon dioxide, they will generally be favoured by policies to limit climate change. Nuclear power will be able to compete economically with electricity from fossil fuels provided the financial risks can be managed [3].

Public acceptance of nuclear power, especially in the USA and Europe, has increased considerably since the mid-1980s. But concerns over safety and nuclear waste may still adversely influence nuclear expansion. Concerns over proliferation issues may slow nuclear development in third world countries. Current management of spent nuclear fuel still relies on interim storage of the high-level waste, but final geological disposal options may become available within a decade in Finland, Sweden and possibly other countries. Reprocessing of spent fuel and transmutation of minor actinides may limit the amount of high-level waste produced, but ultimately the waste will need to be buried in geological repositories.

Generation IV fission reactors

The three existing generations of nuclear reactors represent an evolution of thermal neutron reactor technology to improve safety and economic performance, but with only minor changes in the basic concepts. Generation III+ emphasises simplified designs, reducing the likelihood of system failure, and greater use of passive safety systems that do not rely on external power.

In 2000, the US DOE initiated the Generation IV International Forum (GIF), which now has 13 members[13], to promote international cooperation in research and development for the next generation of nuclear energy systems. Reactor designs should be competitively priced while satisfactorily addressing nuclear safety, waste, proliferation and public perception. With enough progress in research and development, first-of-a-kind Generation IV reactors could be developed around 2030, with commercial deployment starting from 2040.

The GIF has chosen six reactor concepts which it believes can meet the requirements (see also Table 8):

1. Sodium-cooled Fast Reactor (SFR)
2. Gas-cooled Fast Reactor (GFR)
3. Very High Temperature Reactor (VHTR)
4. Super Critical Water-cooled Reactor (SCWR)
5. Lead-cooled Fast Reactor (LFR)
6. Molten Salt Reactor (MSR)

Three of these systems (SFR, GFR and LFR) are based on fast neutrons, one on epithermal neutrons (MSR), and two operate with thermal neutrons (VHTR and SCWR), like today's nuclear power plants. The fast and epithermal neutron reactor systems all employ closed fuel cycles to maximise fuel utilisation and minimise high-level waste. Operating temperatures range from 500°C to 1,000°C, compared to about 300°C in present-day light-water reactors. The high temperatures increase the thermal efficiency of electricity production, and would open up the possibility of producing liquid chemical fuels and for thermo-chemical hydrogen production.

The three fast-neutron reactors on the list also address concerns about proliferation. In contrast to conventional fast breeders, they do not have a blanket assembly producing Pu-239; instead, plutonium breeding takes place in the core, where burn-up is high and Pu-240 is produced. Pu-240 produces penetrating and intense gamma radiation, making it difficult to divert to nuclear weapons. In addition, new reprocessing technologies may enable the fuel to be recycled without separating the plutonium.

[13] *USA, Argentina, Brazil, Canada, China, France, Japan, Russia, South Korea, South Africa, Switzerland and the UK are charter members of the GIF, along with the EU (Euratom).*

Table 8
Basic design data for the six Generation IV reactor candidates

	Neutron spectrum	Coolant	Temperature (°C)	Pressure	Fuel	Fuel cycle	Size (MW_e)	Uses
SFR	Fast	Sodium	550	Low	U-238 & MOX	Closed	300–1,500	Electricity
GFR	Fast	Helium	850	High	U-238+ Pu-239	Closed	1,200	Electricity and hydrogen
VHTR	Thermal	Helium	900–1,000	High	UO_2 prism or pebbles	Open	250–300	Electricity and hydrogen
SCWR	Thermal	Water	510–625	Very high	UO_2	Open	1,000–1,500	Electricity
LFR	Fast	Lead or Pb-Bi	400–800	Low	U-238+ Pu-239	Closed	600–1,000	Electricity and hydrogen
MSR	Epithermal	Fluoride salts	700–800	Low	UF in salt	Closed	1,000	Electricity and hydrogen

The SFR technology is the most mature of the Generation IV reactor systems, as it builds on more than 300 reactor-years of experience. It may enter commercial operation even before 2030. In Europe, SFR is the reference fast-reactor system, with GFR and LFR selected as alternative technologies to be assessed [4]. The USA is focusing on VHTR.

Fission fuel cycle

The naturally occurring fuel resources for fission nuclear power are uranium and thorium. The world's known reserves of cheap uranium (up to $130/kg U) are very roughly 60 times the current annual consumption, so there is little incentive for further prospecting. Moreover, several factors could considerably extend fission resources in the long term.

First, it is conservatively estimated that at least 10 and perhaps 100 times more terrestrial uranium is accessible at moderately higher cost, still low enough that it would make up only a tiny fraction of the overall cost of electricity. Second, fast-neutron reactors and recycling of spent fuel can increase the amount of energy extracted from the uranium ore by a factor of probably 20-50. And if these resources fail, uranium is present in sea water at levels (roughly three parts per billion) that in the long term may become economically viable to extract.

Fission is therefore sustainable for thousands of years, even at substantially higher rates of use. There is no prospect that resources of fission fuels will become strained by 2050, though increased fission use may call for additional ore-processing and uranium enrichment facilities. Thorium resources are comparable to those of uranium, but their geographical distribution is different.

Light-water reactors (LWRs) require the uranium in which the natural level of U-235, the fissionable isotope of uranium, is about 0.7% to be enriched to a few per cent. This is currently done most efficiently by gas centrifuges. Proposed alternative schemes such as laser isotope separation might reach commercial scale by 2050, but concerns about proliferation discourage government investment, and existing technology is fully adequate.

The enriched uranium is fabricated into fuel for LWRs, generally in the form of rods containing uranium oxide pellets encased in zirconium. The fuel provides energy in an operating reactor for about one to three years, after which it is considered spent and removed. The remaining radioactivity in spent fuel decays quite rapidly: LWR fuel generates about 12 kW of heat per tonne of fuel one year after it leaves the reactor, but after ten years this has fallen to 2 kW/t. Spent fuel is generally kept in ponds of cooling water for the first ten years, after which it can be transferred to robust dry-storage casks.

In some countries, notably France, Japan, the UK and Russia, fuel is reprocessed to extract the remaining uranium and the plutonium which has been generated in the fuel. These materials are recycled into mixed oxide fuel (MOX) and reused in reactors.

Building new reprocessing plants is not economical: The fuel they produce would be more expensive than new fuel from uranium ore, and because uranium is almost certain to remain abundant, this situation will probably not change by 2050. Since capital costs dominate the economics of reprocessing, it may, however, make sense to continue to run existing reprocessing plants at full capacity. Otherwise the once-through fuel cycle will generally remain the most economic option even by 2050. Policy preferences might nevertheless favour reprocessing to improve uranium resource utilisation and to reduce high-level waste.

In the longer term, the continued use of nuclear fission will eventually encourage the breeding of fissile isotopes from U-238 and subsequent reprocessing to extract the large extra amounts of energy these isotopes contain. Prudent management of resources suggests that, for now, we should store used fuel in ways that would allow it to be retrieved for future reprocessing.

New reactor designs for new applications of nuclear power, for example to provide high-temperature process heat, liquid chemical fuels or nuclear breeding, will almost certainly require new types of fission fuel. The timescale for commercialising these new types of reactors and fuels is typically 10-20 years, so if public opinion favours new nuclear capacity, we can expect to see wider application new-generation reactors coming into use in the 2050 timeframe, together with the fuel facilities to support them.

Fusion energy

Nuclear energy from controlled thermonuclear fusion has the potential to provide an environmentally friendly and almost inexhaustible energy source for humanity. Fusion energy, which powers our sun and the stars, is released when light elements such as the hydrogen isotopes deuterium and tritium fuse together. This occurs at very high temperatures, where all matter is in the state known as plasma.

Open and globally coordinated fusion research started 50 years ago. It was realised early on that building a reliable fusion power plant would be extremely challenging, but the prospect of fusion power is attractive enough to make the necessary research worthwhile. Fusion promises safe, clean, zero-carbon energy from a fuel that is abundantly available everywhere.

The many challenges lie predominantly in confining the plasma particles and energy tightly enough and for a sufficiently long time for producing excess energy by the fusion processes. Aside from issues of plasma physics, this requires the development of new materials which can resist large neutron fluxes and high power loads without becoming dangerously radioactive.

A fusion reactor carries no risk of a runaway nuclear reaction, since optimal conditions are needed for the plasma to ignite, and any change in these conditions will stop the production of excess energy. Furthermore, the total amount of fuel in an operating reactor is very small – typically a few tens of grammes – so the fusion reaction will stop within seconds once the fuel supply is cut off. As a further safety factor, the energy stored in the plasma is insufficient to destroy the system's safety barriers.

Several schemes for achieving fusion energy have been suggested over the years [5]. Currently, two concepts seem capable of confining the hot plasma sufficiently well to produce useful power: magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).

Magnetic confinement

Among the various MCF configurations that have been tested, the tokamak, which confines the plasma in a doughnut-shaped chamber – a torus – surrounded by electromagnets, is now close to operation with net production of energy. The Joint European Torus (JET) [6] in the UK is run jointly by the European Fusion Associations. As early as 1997, JET produced a peak of 16.1 MW of fusion power, corresponding to 65% of the input power needed to maintain the plasma, and sustained power production for half a second.

Based on the results from JET and several other tokamaks worldwide, fusion research is now taking the next step: the construction of a large-scale R&D tokamak, ITER, [7] in France. The construction of ITER, expected to finish in 2020, is a worldwide collaborative effort. The purpose of the project is a scientific demonstration of a self-sustaining controlled fusion reaction.

Further into the future, a facility known as DEMO will build on experience from ITER to demonstrate significant net electricity production (several hundreds of MW) from fusion for an extended period of time. DEMO is also intended to test and qualify key fusion reactor components under realistic operating conditions. After, DEMO would become the first commercial fusion power plant (FPP). The generally accepted roadmap towards fusion power envisages ITER burning plasma by 2026; DEMO being built 2030-2040 and operating 2040-2050; and (optimistically) a first FPP in operation by 2050.

Inertial confinement

The basic principle of inertial confinement fusion (ICF) is to confine and compress the plasma using focused beams such as high-energy lasers. The most direct method is to compress a millimetre-sized pellet containing a mixture of deuterium and tritium.

The laser energy delivered to the surface of the pellet compresses the fuel, creating a shock wave which heats the centre of the pellet to a temperature at which fusion can take place. As fusion begins, it releases energy which further heats the surrounding fuel and so accelerates the fusion processes. The goal is to achieve a self-sustaining reaction rate ("ignition") with an energy gain high enough eventually to allow net electricity production.

Experiments have demonstrated significant compression and heating of the fuel pellet, but ignition has still not been achieved. The newly opened American National Ignition Facility (NIF) [8] experiment has obtained promising results, and it is predicted that ignition will be demonstrated within the next year, marking a significant milestone for ICF.

Apart from the ICF activities in the USA, significant work is being done in Japan and Europe. The European project is the High Power Laser Energy Research Facility (HiPER, www.hiper-laser.org), which is presently in the design phase with construction planned to start in 2015. HiPER is designed to demonstrate a promising concept known as fast ignition, which should lower the energy input needed from the laser driver. Despite significant activity in ICF, most researchers believe that building the first ICF power plant will take at least as long as the first MCF plant.

Taking an optimistic view, the first energy-producing fusion reactors will be available around 2050. After that, fusion energy is expected to become increasingly important during the second half of the century, and to make a significant contribution by 2100. The power plants now being discussed [9] will typically be around 1-1.5 GWe – equivalent to large fission power plants. The successful development of fusion reactors will, however, require continuous, strong and dedicated involvement from industry as well as public research institutions.

Conclusions

With concerns over the emission of GHGs and increasing international focus on securing stable and economically viable energy supplies, nuclear energy will continue as an important part of the global energy mix. The nuclear share of electricity production could rise to 20% or more by 2050.

The extent to which nuclear energy will contribute is influenced by political and economic factors, including setting a price on carbon emissions, the ability to constrain proliferation risks, public acceptance and the availability of capital to build new plants. Public acceptance will be aided by the continued safe running of nuclear power plants and the development of safe and acceptable repositories for nuclear waste. In the longer term, new high-temperature fission reactors may become available for energy applications other than electricity, further expanding the demand for nuclear power.

Nuclear power is not part of current Danish energy planning. Whether this will remain the case in 2050 is basically a political question: Is Denmark willing to depend on imported electricity to complement local production from renewables, and are we willing to pay the additional costs? If the answer to either of these questions is no, Denmark in 2050 could have a limited number of fission reactors to supplement its high proportion of renewable energy while ensuring a low carbon footprint.

Fuel resources for nuclear fission will remain available for centuries to come, even using current technology. Successful implementation of Generation IV technology with closed fuel cycles would ensure that we have enough fuel for thousands of years.

Fusion power holds great promise for the future, but also poses great challenges. Its implementation requires advancement of plasma confinement science and development of specific fusion engineering technology. If successful, fusion will provide energy for thousands of years, with less radioactive waste than fission power. The development of both fusion energy and future Generation IV fission technology will require new advanced materials. The successful implementation of these technologies will also require a new generation of scientists, engineers and regulatory experts. The research required to develop these technologies is so advanced that no single institution or nation can support the complete process. Only with concerted action from industry, politicians, regulators and research institutions can advanced nuclear technologies fulfil their promise.

12
Carbon capture and storage

Mikael Lüthje, Risø DTU, Denmark

Introduction to CCS

Carbon capture and storage (CCS) is a way of reducing the amount of carbon dioxide (CO_2) released by large industrial plants burning fossil fuels. Most or potentially all of the CO_2 present in the flue gas can be captured, after which it is compressed and pumped into geological reservoirs, onshore or offshore, for long-term storage. The technologies for the individual steps in CCS already exist and are rather well known, and there is proven geological storage capacity for large-scale implementation.

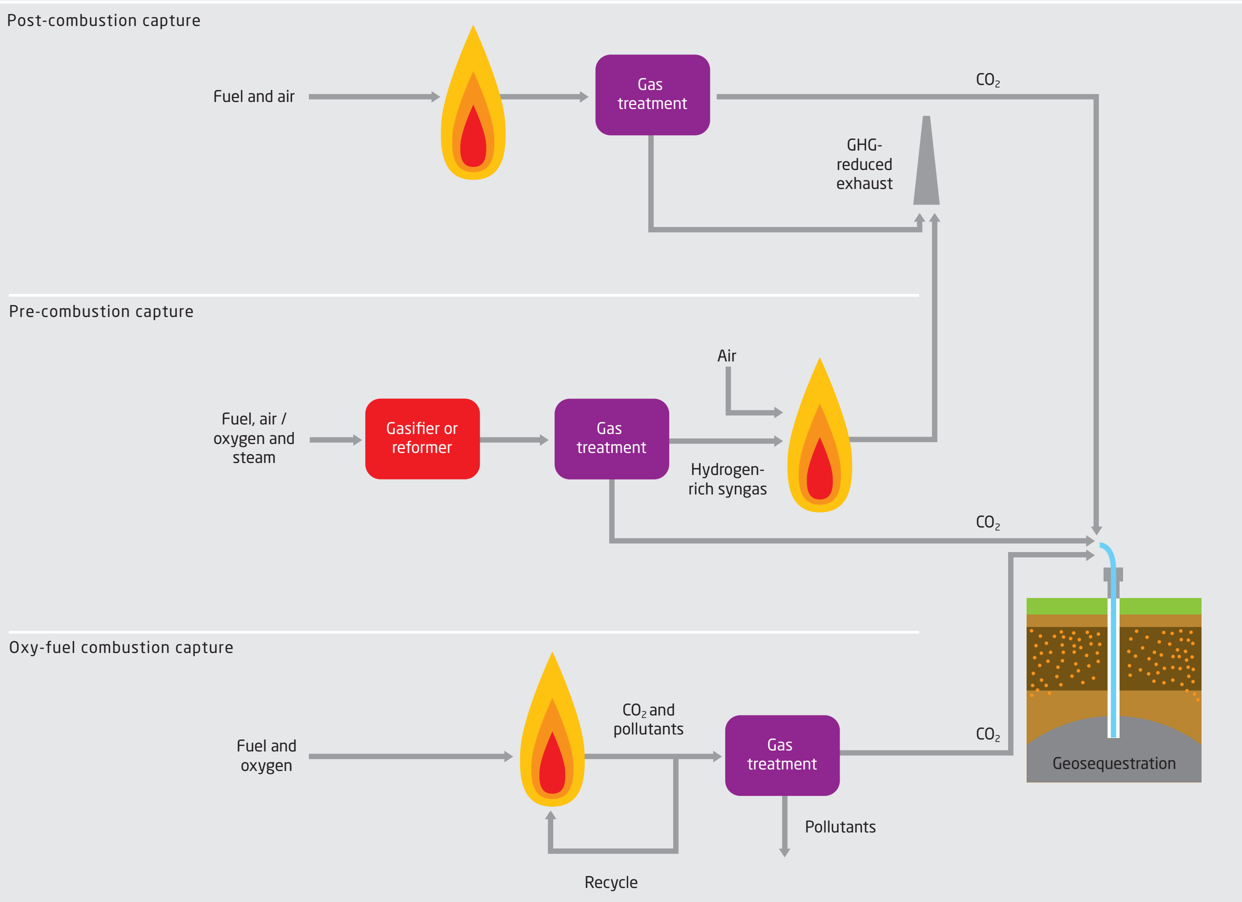
The International Energy Agency (IEA) estimates that CCS could reduce the worldwide emissions by 10 Gt CO_2/yr, and that the cost of achieving climate stability[14] by 2050 would be at least 70% higher without CCS [1]. In future, CCS fitted to biomass-fired power and industrial plants could be used to decrease the atmospheric concentration of CO_2.

Capture

CCS can be used on large "point sources" of CO_2 such as power plants and large industrial furnaces. In general, there are three approaches to capturing the CO_2: post-combustion, pre-combustion and oxy-fuel combustion (Figure 38).

In post-combustion capture, the CO_2 is separated from the flue gas produced by combustion of the fuel. The most common way of doing this is by scrubbing the flue gas with an amine solvent to absorb the CO_2, which is then recovered from the solvent in a regeneration stage. Impurities such as particulates and oxides of sulphur and nitrogen must be removed before CO_2 scrubbing. The technology can be retrofitted without major changes to existing power plants if the layout and space requirements allow it, but has rather high running costs.

Figure 38
The three approaches to CO_2 capture. Source: [2]



Legend
CO_2 - Carbon dioxide
GHG - Greenhouse gas

[14] *50% reduction in CO_2 emissions, compared to 2005, by 2050.*

In pre-combustion capture, the CO_2 is removed before combustion takes place. The fuel is either steam-reformed or partially oxidised to create a synthesis gas (syngas) composed of hydrogen and carbon monoxide (CO). The carbon monoxide is further converted to CO_2 in a shift conversion by the addition of steam. After removing the CO_2, the remaining hydrogen-rich gas is burned to generate power or alternatively used in fuel cells. The technology has been used for a long time, but not on the scale required for CCS, and the investment cost is rather high.

Oxy-fuel combustion capture uses pure oxygen for the combustion process. Compared to combustion in air, this results in a much smaller volume of flue gas consisting largely of water vapour and CO_2. The water vapour is easily removed by cooling and condensation, and after treatment to remove other pollutants, the resulting gas is nearly pure CO_2. The main drawback is the need to use pure oxygen, which carries a large energy penalty.

Transport and storage

The captured CO_2 is compressed to its supercritical phase which can be transported by pipeline or ship.

Extensive commercial experience in handling CO_2 in pipelines already exists from projects using CO_2 in enhanced oil recovery (EOR) projects. In the USA alone, around 2,500 kilometres of pipelines transport 50 Mt CO_2/yr ([3], [4]). The pressure during transport is typically kept above 100 bar, and long pipelines require recompression stations along their lengths. Corrosion can be a problem if the CO_2 is not carefully dried.

In general, the transport price per tonne of CO_2 falls rapidly as quantities increase; CO_2 is cheaper to transport by pipeline than by ship except over very long distances [3]. However, transport by ship is very flexible and can be cost-effective, especially in the emerging phase of CCS.

The captured CO_2 can be stored or used in several ways. It can be used to grow algae in closed tanks, or to boost the productivity of forests. It can be locked up in soils or minerals, or injected deep into the ocean or geological formations. Of these options, only ocean and geological storage have the potential to take up very large amounts of CO_2. However, over time, CO_2 stored in the oceans will reach chemical equilibrium with the atmosphere. Ocean storage will therefore reduce the atmospheric CO_2 level for several centuries but not on the long timescale (millennial). CO_2 in suitable geological formations, on the other hand, should remain locked up for millions of years.

CO_2 can be stored underground in sedimentary structures such as saline aquifers, depleted gas and oil fields, and deep coal seams. Saline aquifers exist worldwide and have the potential to store very large amounts of CO_2. However, the effect of CO_2 on aquifers and the geology is not as well known as for depleted oil fields, where injected CO_2 can fill the empty spaces left by the removal of hydrocarbons. Since these reservoirs have stored oil and gas for millions of years, they are promising locations for CO_2 storage.

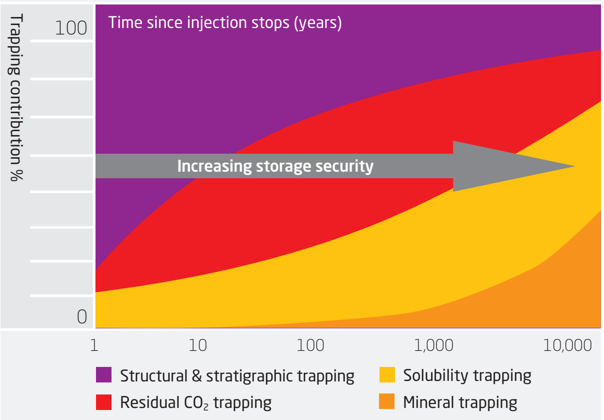
CO_2 in deep coal seams is stored in pores on the surface of the coal and in fractures. As well as providing storage, CO_2 injection could increase the recovery of coal-bed methane in a similar way to its use in EOR in conventional oil fields. This application of CO_2 injection is very likely to increase in future.

CO_2 is not a poisonous gas but is an asphyxiant in large concentrations so proper monitoring should be in place. However, the risk of leakage from properly chosen geological storage sites is very small. The risk also decreases with time, because over timescales ranging from days to thousands of years, several processes combine to lock the CO_2 in place with increasing permanence.

CO_2 injected into a suitable geological formation is less dense than the surrounding liquids, so it percolates up through pores in the rock until it is trapped by an impermeable layer of cap-rock at the top of the formation (Figure 39). As it moves through the rock pores, some of the CO_2 is left behind as residual droplets in the pore spaces. These droplets are immobile, so the overall risk of leakage falls.

CO_2 also dissolves in the brine already present in the rock pores. The resulting solution is denser than the surrounding fluids, so in time it sinks to the bottom of the formation, trapping the CO_2 even more securely. The final phase,

Figure 39
The different stages of CO_2 trapping. When first injected, CO_2 is trapped by impermeable cap-rock and as residual droplets in the pore space. Over time, some of the CO_2 will dissolve in the brine, and eventually more CO_2 will be locked up by reacting with minerals. Source: [3]

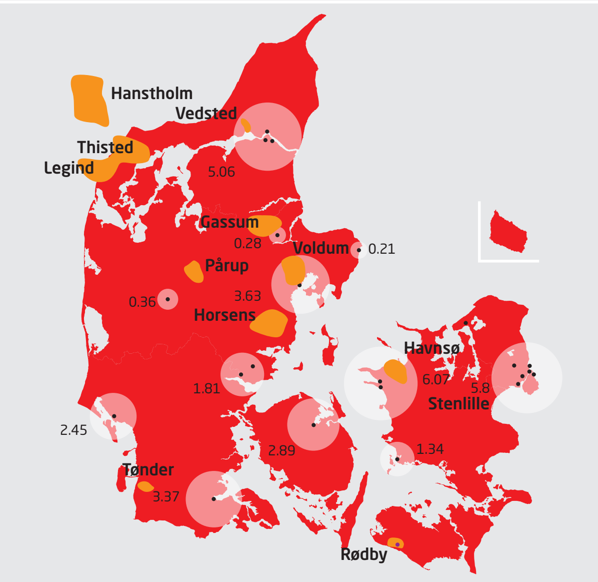


mineral trapping, results from the fact that CO_2 dissolved in water forms a weak acid (carbonic acid). Eventually this acid reacts with the surrounding rock to form solid carbonate minerals which are extremely stable.

Estimating storage potential

Denmark has extensive potential for storing CO_2, especially onshore. Saline aquifers both onshore and offshore have an estimated capacity of nearly 17 Gt (Figure 40), with a further 800 Mt in old oilfields in the Danish sector of the North Sea [5]. For comparison, the country's ten largest point sources of CO_2 emit 21 Mt CO_2/yr between them, so Denmark could potentially store all its CO_2 for hundreds of years.

Figure 40
The largest potential sites for Danish underground CO_2 storage (excluding hydrocarbon fields in the North Sea), and the largest emitters. Source: Geological Survey of Denmark and Greenland



Calculating CO_2 storage possibilities worldwide is not straightforward, and estimates vary from hundreds to tens of thousands of gigatonnes [6]. For the EU countries, more detailed studies indicate a storage capacity of several hundred gigatonnes (Table 9) [7].

CO_2 emissions from large point sources in the EU are of the order of 2 Gt CO_2/yr, and around 15 Gt CO_2/yr worldwide, so in principle there is enough capacity to store all emissions for a very long time. However, the locations of emissions and potential storage sites do not always coincide so a few countries will not have the storage capacity they need for their own CO_2 emissions.

The cost of CCS

The main cost of CCS lies in the capture stage, both in the capital cost of the CCS equipment and the loss in efficiency of the power plant. The costs of transport and storage, while substantial, are lower (Table 10). The fuel use for the capture alone increases by 10-25%, and expressed in terms of increased power prices, the total extra cost of CCS is 0.01-0.05 \$/kWh[15] [3].

Table 10
CCS prices (CO_2 abated) for an early commercial reference case around 2020. Capex refers to capital expenditure and Opex to operating expenditure. The figures do not refer to any specific technology. Source: [9]

	€/t CO_2	Notes
Capture	25-32	Capex: 14-19 Opex: 5-7 Fuel: 2-6
Transport	4-6	Capex: onshore 4, offshore 6 Opex: 0.1
Storage	4-12	Capex: onshore 3-4, offshore 10-11 Opex: 1

The overall cost of CCS is estimated at €60-90/t CO_2 during the demonstration phase, falling to €35-50/t CO_2 during the early commercial phase (2020–2030) and to €30-45/t CO_2 after 2030, once the technology is commercially mature. All prices are per tonne of CO_2 abated ([3], [9]). All these costs are on top of the original cost of electricity, and whether CCS is economical depends on the future price of CO_2.

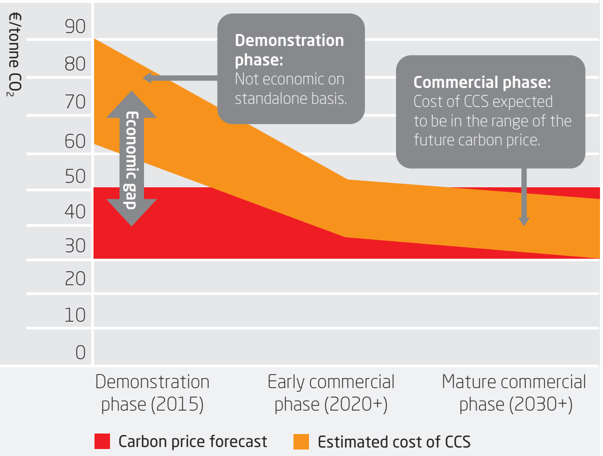
Table 9
Estimates of CO_2 storage capacity in hydrocarbon fields, saline aquifers and coal seams. Based on data from [3], [7], and [8]

Location	Hydrocarbon fields (Gt)	Saline aquifers (Gt)	Coal seams (Gt)
Denmark	0.2-0.8	2.6-16.7	–
EU	30	325	1.5
World	675-900	1,000-10,000	3-200

[15] *Calculations based on technology available in 2002.*

However, if a 50% reduction in CO_2 emissions (compared to 2005) is to be reached by 2050, the cost would be at least 70% higher without CCS ([1], [10]). To reach this target, an investment over the coming 40 years in the power sector alone of around $2.5 trillion is needed, and by 2020, 100 CCS projects should be running. At present, low CO_2 prices make CCS demonstration projects too expensive, so extra funding is required (Figure 41).

Figure 41
Estimated development of the cost of CCS. Source: [9]



On top of this, some issues remain to be solved. Public and political support is often lacking, especially for onshore storage. Legal issues must also be resolved, since CO_2 could be classified as waste, and this could cause problems for storage and transport. The question of liability would also have to be clarified to cover the unlikely event of a serious CO_2 leak.

At present, there are no fully-integrated commercial power plants with CCS, but a few large-scale commercial CCS projects are in operation. These include Sleipner in Norway (1 Mt/yr), Weyburn in the USA/Canada (3 Mt/yr, used for EOR) and In Salah in Algeria (1 Mt/yr). In Denmark, DONG Energy temporarily captured CO_2 from 0.5% of the flue gas at its Esbjerg power plant as part of the European CASTOR project. Vattenfall also had plans to fit CCS to the Nordjyllandsværket power plant in northern Jutland and store the CO_2 in a nearby onshore aquifer, but has postponed the project, partly due to negative public opinion.

Several countries have announced funding for new CCS projects. The USA is funding twelve projects with budgets totalling $1.4 billion, and Canada has four projects worth nearly $2 billion investigating the use of CO_2 for EOR as well as storing it. The UK is on its way, with four demonstration plants receiving more than €100 million. The EU has set aside €1 billion in total for CCS demonstration projects, plus a further sum – currently corresponding to around €5 billion – from the auction of 300 million permits under the emissions trading scheme (ETS). Australia, Korea and Japan have also committed to a number of CCS projects.

Conclusions

To provide a realistic chance of meeting the required CO_2 reduction targets, CCS must be used worldwide, and full-scale demonstration projects must be accelerated to drive down the cost of CCS. The proven reserves of fossil fuels, especially coal, will far outlast this century, and in order to continue using these reserves without adding CO_2 to the atmosphere, CCS is essential. Indeed, adding CCS to biomass-fired plants would be an effective way of cutting atmospheric CO_2.

Technologies for the three individual steps in CCS (capture, transport and storage) have already been developed, and proven geological storage capacity exists for the large-scale implementation of CCS. However, CCS technologies still need further refinement through demonstration plants. Public opinion of CCS has in some cases been negative enough to stop projects going ahead, so this position should be improved through public information or sidestepped by storing CO_2 offshore.

Denmark still has a good chance of becoming one of the leaders in CCS. The country has plenty of geological storage capacity both onshore and offshore and great potential to combine the offshore storage with EOR in the coming decades. Alongside the planned increase in wind energy, coal-fired power plants with CCS could provide the baseload until biomass-fuelled power plants – also with CCS – are ready to take over. Other countries are investing heavily in CCS, however, and without the funding and support that is currently lacking, Denmark will have trouble keeping its current position.

13
System aspects

Ulrich Wagner, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany; Robert Schock, World Energy Council, UK; Hans Larsen and Leif Sønderberg Petersen, Risø DTU, Denmark

Introduction

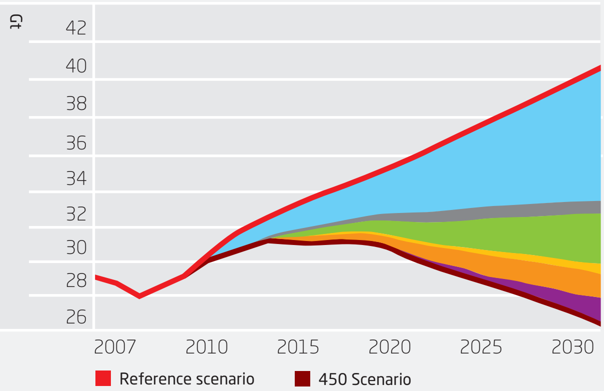
The energy systems of today have developed gradually over the past 100 years or more. This evolutionary process has created energy systems based primarily on central production units which deliver electricity through transmission lines, from there to distribution networks, and finally to end-users.

Future energy systems will have to be much more sophisticated, with both central and decentralised generating units intelligently linked to end-users. This will take decades to achieve in industrialised countries. Intelligent energy systems could be developed more rapidly in developing countries with fast-growing economies, as these countries have to invest in a new infrastructure.

In its World Energy Outlook 2009 [1], the IEA points out that many different initiatives are needed simultaneously covering both end-use, efficiency improvements and new supply technologies if we are to limit the future atmospheric concentration of greenhouse gases to 450 ppm CO_2eq. According to the 4th Assessment Report from the Intergovernmental Panel on Climate Change, this figure is needed to limit the global mean temperature increase to 2°C.

Electricity will play an even more important role in this new energy world, thanks to its ability to be created from a variety of energy sources, its ease of transmission and its convenience to end-users. Research and development in new technologies for creating, transporting and using electricity is essential, and at a greatly expanded scale.

Figure 42
Efficiency measures account for two-thirds of the 3.8 Gt of CO_2 abatement required by 2020 to meet the 450 ppm CO_2eq target. Renewables would contribute close to one-fifth. Source: WEO 2009



	Abatement ($Mt CO_2$)		Investment ($2008 billion)	
	2020	2030	2010-2020	2021-2030
Efficiency	2,517	7,880	1 999	5 586
End-use	2,284	7,145	1,933	5,551
Power plants	233	735	66	35
Renewables	680	2,741	527	2,260
Biofuels	57	429	27	378
Nuclear	493	1,380	125	491
CCS	102	1,410	56	646

New energy supply technologies such as photovoltaics, and new highly efficient end-uses, are certain to influence the economics and sustainability of energy systems. However, the implications of technological development on the supply and use of energy, and on the enabling technologies used by future energy systems, are still uncertain.

We cannot create the energy systems of the future, or significantly reduce our primary energy consumption, by incrementally improving individual components of the present systems. Instead, we need to integrate and optimise the entire system – production, conversion to an energy carrier, transport and distribution of the carrier and the efficient end-use of energy, better matching the energy quality of demand and supply type – and back this up with stable energy policies. We need a paradigm shift to create revolutionary change so that, for instance, consumption adapts automatically to the changing availability of all energy sources or carriers.

However, new energy carriers such as hydrogen or hydrogen-rich biofuels could supplement (or compete with) electricity in the years up to 2050. Efficiency improvements in the conversion, transmission and use of energy are expected to take place at all levels.

Energy conversion and storage

Sustainable electricity generation technologies can be developed to a higher level of efficiency than we know today. Besides steady development in conventional thermal power plants, for instance with cycles operating above 700°C, there is great potential for improving the newer technologies. Examples include the aerodynamic optimisation of wind turbines, new photovoltaic cells, new materials for fuel cells and second-generation biomass conversion processes.

New low-temperature processes also need to be developed and brought to market. These systems have huge technical potential for generating power from geothermal and waste heat, but their efficiency, availability and economics first need to improve significantly.

In general, primary measures such as improvements in energy efficiency are always preferable to secondary measures such as CCS, which is highly energy-intensive and not likely to provide a sustainable solution in the long term.

Storage technologies aimed at ensuring flexibility in future energy systems include hydrogen, pumped hydro, large batteries and compressed air energy storage (CAES). Challenges in the management of energy supply exist on both long and short timescales. The long end of the spectrum (hours, days or more) covers independent fluctuations in both electricity demand and renewable energy supply, while the short term (minutes to hours) is concerned with imbalances created by uncertainty in predicting supplies of renewable energy, such as wind and solar power. Large-scale electricity storage would be able to shift demand and supply, helping to balance the power system at all timescales, and could therefore play an important role in future intelligent power systems.

Recent years have seen extensive discussion of a hydrogen economy. Among some experts, there have been great expectations of the use of hydrogen as a carrier for alternative fuels, especially in transport and as a storable form of electricity. Developing the associated infrastructure will require huge investments and new technological solutions. However, there is a long-standing debate among experts whether a hydrogen economy will indeed play a large role, or other alternatives (such as electric ones) develop further to prevent the need for such massive infrastructural changes. So it seems unlikely that hydrogen will make a major contribution before the middle of the century.

Transmission and distribution

The natural gas grid

Natural gas is often highlighted as an important enabler in the transition towards a low-carbon society. The low carbon content of methane relative to coal and petroleum means that gas demand will continue to expand: The WEO's 450 ppm scenario predicts that world primary gas demand will grow by 17% between 2007 and 2030, though the figure for 2030 is 17% lower than in the WEO's reference scenario. Most gas-importing regions, including Europe and developing Asia, will see their net imports of natural gas rise (WEO 2009).

Global proven gas reserves at the end of 2008 totalled more than 180 trillion cubic metres (tcm), equal to about 60 years of production at current rates. The long-term global recoverable gas resource is estimated at more than 850 tcm.

In view of the above, it is not surprising that the world is investing in expanding natural gas grids. In Europe, a new and important gas pipeline is Nord Stream, which will link Russia and the EU via the Baltic Sea. The first line is due for completion in 2011. Natural gas grids will play a major role in most regions of the world through 2050.

District heating and cooling

District heating and cooling (DHC) grids, like natural gas grids, are often deemed to facilitate GHG reduction. Many countries with a tradition of DHC are renewing their commitment as they find new ways of using the technologies to reduce environmental impacts. DHC facilitates environmentally desirable links between energy supplies that would not otherwise be available to end-users.

District heating is a flexible technology as it can make use of any energy source, including waste heat, renewables, geothermal energy, and most significantly combined heat and power (CHP). Denmark has, along with former communist countries, been a leader in DHC for a long time.

The European CHP+ technology platform imagines that by 2050 district heating and cooling networks will constitute widespread systems of energy exchange. In this vision, DHC will be part of the infrastructure of most European cities and towns, installed together with other basic networks. Interconnected local grids will create regionwide DHC networks. Heating and cooling would be based solely on low-carbon renewable energy sources or those using state-of-the-art carbon abatement, so the network would offer customers a carbon-neutral solution for both heating and cooling [2].

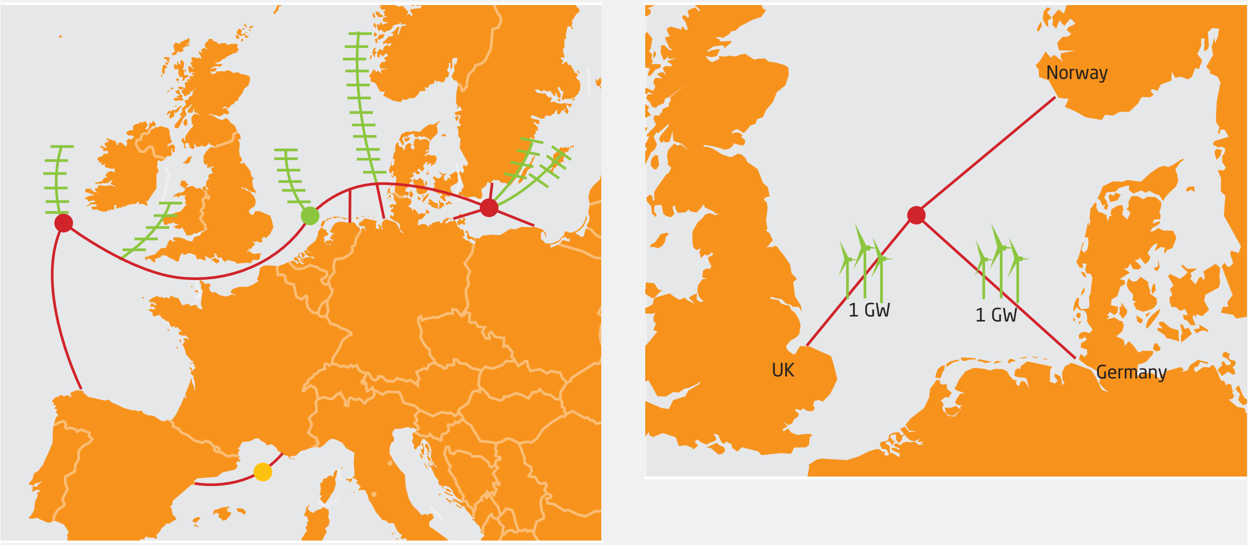
DHC seems to have a role in the long run, but it faces a challenge in the development of new energy-efficient houses. These have low annual energy demands, but not necessarily low peak demands, and could thus require DHC networks to be oversized for much of the time. However, if buildings become very low or zero-energy, DH/DHC networks will likely not be economical any more.

Supergrids

"Supergrids" based on high-voltage direct current (HVDC) technology are attractive because they offer the controllability needed to transmit varying amounts of wind power and to act as highways for electricity trade, even between different synchronous zones.

The ultimate, global, supergrid would be able to balance power consumption, by operating across different time zones, and generation, because somewhere in the world the sun is always shining and the wind is always blowing.

Figure 43
The SuperNode configuration could be a first step towards a European supergrid. It would allow the three-way trading of power between the UK, Norway and Germany, and would include two 1 GW offshore wind farms, one in the UK and one in Germany. To balance fluctuations in wind power, up to 1 GW could be transferred between any two of the three countries [6].



Although primarily installed offshore, supergrids could include onshore nodes that might avoid the need to reinforce existing onshore grids close to the coast [3]. It is worth nothing that the need to build new onshore transmission lines may be a limiting factor in building large offshore wind farms, due to public resistance and legal problems in obtaining the necessary rights of way. To make sure that construction costs are shared fairly, we should agree now on the roadmap for building these grid extensions.

The planned European offshore supergrid will allow electricity to be transmitted easily between the grids of participating countries (Figure 43). In December 2009, the UK, Germany, France, Belgium, the Netherlands, Luxembourg, Denmark, Sweden and Ireland launched the North Seas Countries' Offshore Grid Initiative to cooperate on infrastructure for wind power in the North Sea and the Irish Sea [4], [5].

Energinet.dk, Vattenfall Europe Transmission and Svenska Kraftnät are investigating an offshore grid linking the national grids of Denmark, Sweden and Germany and connecting these to the planned international wind farm at Kriegers Flak in the Baltic Sea.

Distribution and flexible grids

At the local level, there is a need for intelligent ("smart") distributed generating systems, especially cogeneration units with climate-neutral fuels based on internal combustion engines or fuel cells. These are highly efficient in any application where electricity and heat are required at more or less the same time, or can be buffered by heat storage. Many CHP units can combine to form a virtual power plant that is centrally controlled, so that it reacts to the overall state of the grid and can even export power over long distances when necessary.

Such a mix of distributed power sources will work best if matched by flexible consumption. Electric vehicles, electric heating, heat pumps, heat storage and small-scale distributed generation from CHP or solar panels together form a promising combination. This flexibility in supply and demand is particularly important for electricity grids, which have almost no storage capacity of their own. It is somewhat less critical for gas, district heating and hydrogen grids, which by their nature include a certain amount of storage.

The combination of three grids – for power, district heating and natural gas – gives Denmark a highly efficient supply system with a large proportion of CHP. Proposed increases in renewable energy, primarily wind power, must interact as effectively as possible with these grids if they are to maximise displacement of fossil fuels in the electricity, heat and transport sectors.

End-use

A future intelligent energy system will depend on end-users to stay in balance. Power demand, for instance, must be highest when plenty of power is available and prices are low – which may well mean when the wind is blowing strongly. New end-user technologies must be introduced on a large scale; an example is houses which are almost self-sufficient in energy, with effective insulation, smart electronic equipment, heat storage, and their own energy supplied by heat pumps, solar energy and small wind turbines. Many future energy users will become increasingly self-sufficient, able to meet all their limited needs for electricity and heat over long periods.

Supplying energy for transport via the power grid has several advantages, such as increased flexibility through closer links between the power and transport sectors, increased energy efficiency, and the chance to include transport-related greenhouse gas emissions in carbon trading schemes. "Transport" here refers not just to cars and lorries but could also cover shipping and air travel.

Higher acceptance of electric vehicles (EVs) will require batteries with better performance: both specific energy to increase range, and specific power for acceleration. An infrastructure for charging vehicle batteries needs to be built up while making sure that power plants and the local distribution grid can handle the resulting load.

Since ultimately it will be preferable to charge EVs using renewable electricity, a central control system has to ensure that batteries are charged when wind or solar power is most abundant. The issue with EVs is not the total amount of energy they use (a million EVs require only 2 TWh/yr), but lack of grid capacity when millions of batteries are being charged simultaneously.

In each EV, meanwhile, an intelligent controller will need to work with the battery management system, the navigation system, the driver and the power grid at the start and end points of the journey to ensure that the vehicle never runs out of charge.

Electricity is traditionally billed at standard rates for each customer, with little effort to adapt consumption to suit varying conditions in the supply system. However, a combination of liberalisation of electricity markets, an increase in renewable power and new communications technologies have made it possible – and attractive – to develop active demand response.

In households, direct electric heating and heat pumps are well-suited to provide demand response, because of the thermal inertia of buildings. In demonstration projects, switching off electric heating for up to three hours has been shown to cause few comfort problems [7]. Several studies have analysed the value of demand response [8], [9].

Today, the welfare gains are too insignificant to motivate end-users, because in most countries the production cost of electricity is small compared to the added taxes and tariffs. Switching to value added taxes, grid payments which vary according to the grid load, and variable tariffs and taxes could stimulate flexible demand and "demand shifting" and smart metering.

Demand flexibility requires smart electricity meters which communicate with the grid and adjust the flow of power to match the supply situation and customer priorities. Smart metering in turn needs communication standards to ensure that the devices connected to the intelligent power system are compatible and a system which can accommodate both scalability (large numbers of units) and flexibility (new types of units).

Integrated systems

Smart distribution systems

Local smart distribution systems will use information and communications technologies (ICT) to link end-users with both local and central energy supply as required. ICT offers a wide range of new ways of using market incentives to optimise the control of the overall energy system, from generation to consumption. For this to work, however, we need a deep understanding of the energy system; in the worst case, the result could even be worse than before, for instance if we overestimate the need for new generating capacity. So we need to focus on better ways of modelling and analysing complex networks on timescales of up to 50 years, corresponding to the life of many parts of the energy system.

Various clustering arrangements have been suggested to manage the increasing penetration of distributed energy resources (DERs). One of these is the virtual power plant (VPP), which aggregates up to 1,000 individual DERs and manages them in such a way that they appear to the system operator as a single, reliable and integrated resource. In some areas, aggregation is already practised with larger units (above 400 kW).

VPPs could be useful in several ways. In the short term, they could act as an enabling technology for small and innovative generating units, allowing these to enter electricity markets which in some countries are restricted to large power plants. In the long term, it may be better for system operators to continue to deal with a small number of generating plants; as DERs become more common, the alternative will be to negotiate production plans, prices and contracts with thousands of small generators. And for small consumers or producers, it may be advantageous to be a member of a larger entity with the resources to handle negotiations and stay abreast of changing regulations. Other aspects which may become issues in future include complex services, forecasting, islanding and security, control and management strategies, and market interaction [10].

Safety, reliability and security of supply

In all energy systems, stability is essential to ensuring that the system operates satisfactorily and serves its customers adequately. Stability is a particular concern in electricity systems if we want to maintain the existing high standard of supply in modern power systems, with a minimum number and duration of blackouts and disturbances.

Power systems are particularly vulnerable for a number of reasons. First of all, they require that voltages and frequencies remain within narrow margins; generators will trip out when there is a power surge or a drop in voltage. Furthermore, the availability of the transmission and distribution grid can be reduced by disturbances such as lightning strikes and accidents.

When renewable energy sources partly replace large central thermal power plants, the inertia of the power system often falls. Fixed-speed wind turbines with directly connected generators do contribute inertia, but typically less so than conventional power plants of the same capacity.

ICT will therefore be important to the successful integration of renewables. The benefits of distributed power systems include increased reliability and greater overall energy efficiency, for instance through better use of waste heat. Of these factors, reliability of service is one of the most important. The rapidly increasing capabilities and falling costs of ICT open the way to two-way communication between end-users and suppliers, making this one of the most important enabling technologies for future power and gas systems. ICT systems can give market signals to both producers and consumers, allowing much more creative models of energy distribution and especially power trading. The latter is becoming increasingly important in stabilising electric grids against the inherently fluctuating nature of much renewable electricity.

A high proportion of renewable energy in the system will require a number of support technologies, including energy storage and load management, to deal with the fluctuating power from, for example, wind turbines. Such systems, in addition to the obvious benefit of providing a cleaner and sustainable environment, have the advantage that it is easy to add generating capacity as required, using local energy resources. The cost of such expansion is predictable over the life cycle of the generating plant, regardless of the price fluctuations and shortages that may affect fossil fuels in future.

The geographical spread of renewable energy sources will become important as they develop. Some renewable sources like wind, solar and wave power are intermittent and need backup from other sources which have inertia or storage. An added problem is that these resources are not evenly distributed throughout the world, and are not necessarily available where they are most needed. It is windier on the west coast of Scotland than in central Germany, for instance, and more solar power can usually be produced in Spain or Africa, e.g. the project Desertech (http://www.desertec.org/), than in Denmark. Hydropower resources are unevenly distributed throughout the world, and so too is biomass. Transport of basic biomass such as straw and wood is very costly, limiting the cost-effective use of such fuels to the vicinity of production unless they can be upgraded locally to liquid fuels which are easy to transport and distribute.

Economics and politics

Low-carbon growth to meet the WEO 2009 450 ppm scenario would cumulatively cost around $10.5 trillion more than the reference scenario in the years up to 2030, in terms of global energy infrastructure and energy-related capital stock.

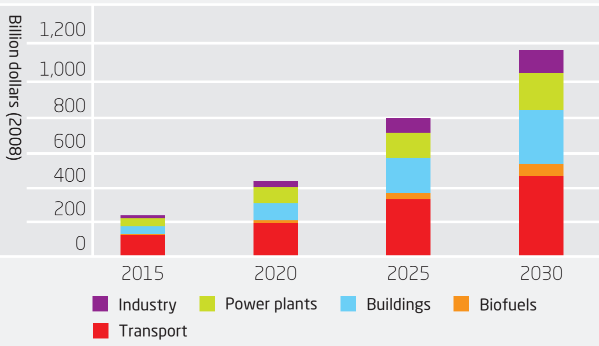
Around 45% of this extra investment would be in transport. The rest would be spent on buildings ($2.5 trillion, including energy-related equipment bought by households), power plants ($1.7 trillion), industry ($1.1 trillion) and second-generation biofuels ($0.4 trillion).

About half the total extra investment would be in the OECD countries, and about a quarter would be needed before 2020.

These costs are partly offset by benefits to economies (lower energy costs), health, avoided climate change and energy security (lower oil and gas imports).

A future intelligent power system requires investment now. An expansion of renewable energy will first need large amounts of money to be spent on improving the transmission system, among other things, and this is not yet happening.
We therefore need stable plans for government investment

Figure 44
According to the World Energy Outlook 2009, stabilising at 450 ppm CO_2eq would need $10.5 trillion of extra investment in the period 2010-2030 compared with the reference scenario. The additional cost is equivalent to 0.5% of global GDP in 2020 and 1.1% in 2030



in the grid, and predictable regulation regimes, to guarantee the improvements in grid performance – both capacity and intelligent control – which in turn will make possible the goal of more renewable energy.

Energy and the environmental policies can strongly impact the development of future energy systems, in both directions. The main rules are:

- Politicians have to determine the overall primary goals. Further parallel goals to be defined, such as amounts of renewables or domestic heating loads, have to be chosen carefully.
- It is important to consider the effect of energy policies on economic, social, security and environmental issues.
- Goals should be stable for long periods, so as to attract investors.
- Cooperation is essential between businesses and governments, between governments and on a regional level.

Conclusion

We cannot get the future energy system we need simply by improving the components of the existing system. Instead, we need an integrated process that will optimise the entire system, from energy production, through conversion to an energy carrier, energy transport and distribution, and efficient end-use.

Similarly, significant reductions in primary energy consumption will not be reached through evolutionary development of existing systems. This will require paradigm shifts and revolutionary changes, such as the automatic adaptation of consumption to match the instantaneous availability of all forms of energy.

In this new energy world, electricity and natural gas will be even more important than they are at present. Electricity is key because of its ability to be produced from a variety of energy sources, transmitted instantly over long distances and used in many different ways, and because of its convenience to end-users. Natural gas is valued for its lower emissions compared to other fossil fuels, and the fact that it can be used as a carrier for hydrogen: Existing stoves and heaters can burn natural gas containing 5-10% hydrogen without needing adjustment.

The rising number of efficient small-generation systems such as fuel cells will create a more decentralised electricity system, especially in cogeneration applications which can use the resulting waste heat. Rising prices for conventionally generated electricity and natural gas, together with falling costs for generation based on renewables, will cause a shift in the structure and use of energy transport and distribution systems. To accommodate the rising number of small virtual power plants, we need to develop a new electricity system with an optimum mixture of central and distributed generators; this is a challenge for the generating technology itself, and even more so for the complex instrumentation and control technologies required for smart metering, demand management and smart grids.

Large-scale and cost-effective electricity storage will form an important part of the future intelligent power system, enabling a balancing of the system over all timescales by shifting demand and supply. Small-scale electricity storage in electric vehicles will also be important to maintaining short-term grid stability as well as controlling demand over longer periods.

An important task of energy system modelling is to maintain up-to-date analyses of all the possible “least-regrets” options, taking into account the constant changes in energy prices, resource availability and politics. Three rules can help us to identify these options:

- diversify primary energy carriers to create flexibility in the energy system;
- increase the efficiency of energy use, even low-power applications, to reduce demand; and
- centralise emissions wherever possible to simplify their treatment.

Scientists and engineers cannot predict the nature of the future energy system, but in certain frames of reference they can help to separate the “no-go” choices from valid least-regrets options. Our children’s children may look back in disbelief that for so long we could tolerate an antiquated energy system without putting in place improvements that were already possible. We are already quite good at the individual components; now it is high time for the bold restructuring that will give us a flexible low-carbon energy system by 2050.

14
Synthesis

Hans Larsen, Henrik Bindslev and Leif Sønderberg Petersen, Risø DTU, Denmark

Introduction

Long-term energy security depends on the continuing availability of fossil fuels and their potential substitution by renewable energy sources. Coal and gas may well dominate the global primary energy supply for the rest of this century if no special effort is made to promote renewables. However, for many countries energy security concerns are accompanied by a preference for renewable options which can reduce their dependence on imported oil and gas, as well as helping to meet environmental policy objectives.

Policies designed to stabilise climate change have some commonality with those for energy security, since both give priority to renewable energy. However, climate change goals can also be met by fitting carbon capture and storage (CCS) at fossil-fuelled power plants, and CCS competes with renewable energy. As a result, global energy studies show that increasing the proportion of renewable energy we use will require extra effort beyond that demanded by climate change.

The increasing interest in green economics and green energy on many nations' political agendas may change underlying assumptions rapidly. Countries like the USA, China and South Korea are aggressively promoting investment in renewable energy and energy efficiency. Given the actual expansion of wind energy installations in various global models, it seems that the fast expansion of wind capacity in the past couple of years is not well reflected in these projections.

To keep the global mean temperature rise below 2°C, we need serious cuts in greenhouse gas (GHG) emissions; according to the IPCC, the necessary reduction in GHGs is 50-60% before 2050. To do this globally while leaving room for development, the OECD countries, including the EU, should reduce their GHG emissions by 80-95% before 2050.

According to the analyses presented in this report, it will be difficult for the European countries to meet these targets as mitigation options from the energy sector alone do not seem to be sufficient, but have to be supplemented by action from other sectors, for example the agricultural sector.

The Danish case described in this report shows that Denmark stands an excellent chance of phasing out fossil fuels rapidly and of reducing GHG emissions at the pace needed to reach global stabilisation at 450 ppm CO_2eq. Denmark's wind and biomass resources, especially, would allow the country to phase out fossil fuels from the production of electricity and heat before 2040.

In Denmark, the combination of three grids – for power, district heating and natural gas – has produced a highly efficient supply system with a high proportion of combined heat and power. The future increase in renewable energy, primarily wind power, must interact as effectively as possible with these grids to maximise the displacement of fossil fuels from the electricity, heat and transport sectors.

Solar

Solar energy technologies either convert sunlight directly into heat and electrical energy or use it to power chemical reactions to create "solar fuels" or other useful materials. Solar heating technologies have developed steadily for many years, and except for traditional biomass, solar heating is among the most abundant renewable energy technologies globally.

In past decades, two technologies for converting solar energy into electricity have dominated: photovoltaics (PV) and concentrating solar power (CSP). The global financial crisis led to a dramatic drop in PV module prices in 2009.

CSP technology has been used in central power plants for more than 20 years in a few installations. Mirrors focus solar radiation on a receiver, and the resulting high-temperature heat is used to generate electricity by driving a turbine or some other engine. Heat can also be used to generate hydrogen from water, and to power more complex chemical reactions producing solar fuels.

Solar energy can be used to generate heat and electricity all over the world. Our technical ability to make use of this resource has improved dramatically in recent years, and by 2050 it is hard to imagine a society that does not rely on solar energy for large parts of its heating and electric power. The IEA forecasts that PV and CSP will each produce 11% of the world's electricity by 2050.

PV is by nature a distributed generation technology, whereas CSP is a centralised technology, so their deployment will follow very different routes. PV is unique among electricity generation technologies in that its distributed nature allows it to be integrated with human settlements of all sizes, urban or rural.

CSP, on the other hand, has advantages and disadvantages common to most centralised generating technologies; so, for instance, new CSP plants will require new electricity transmission capacity. CSP also has some advantages of its own: The fact that most CSP systems separate the harvesting of energy from the electricity generation step allows them to store energy in the form of heat, and to generate power from other fuels when the sun is not shining.

Wind

Since 1970, wind energy has grown at spectacular rates, and in the past 25 years, global wind energy capacity has doubled every three years. The current wind energy capacity of approximately 160 GW is expected to generate more than 331 TWh in 2010, covering 1.6% of global electricity consumption. Approximately 2% of the capacity installed during 2009 was offshore, bringing the total offshore capacity to 2.1 GW, or 1.3% of global wind energy capacity.

Onshore wind has enormous potential: at almost 400 EJ/yr. An estimate of 22 EJ/yr for offshore wind potential is conservative, as it includes only wind-intensive areas on continental shelves outside shipping lines and protected areas.

Most of the development effort so far has been dedicated to the evolutionary scale-up and optimisation of the land-based three-bladed standard wind turbines which emerged as commercial products at the beginning of the 1980s. With increased focus on offshore deployment combined with the radically different conditions compared to onshore, it is likely that completely new concepts will emerge, such as the vertical-axis turbine currently being developed at Risø DTU.

Offshore exploitation represents an even bigger challenge for wind turbine development, operation and cost-optimisation. It also brings new potential, since wind resources offshore are generally higher, and many of the constraints are very different to those onshore.

In energy scenarios involving large proportions of wind power, wind should be seen as a baseload-generating technology. For instance, in an integrated power system comprising wind and hydropower, and possibly high-efficiency pumped storage too, the best use of wind power is to deliver the baseload.

The coming decade may see new technological advances and further scale-up, leading to more cost-effective, reliable and controllable wind turbines and new offshore and onshore applications, including the introduction of wind power in the built environment. Wind energy has the potential to play a major role in tomorrow's energy supply, cost-effectively covering 30-50% of our electricity consumption.

Hydropower and wave power

Hydropower is a mature technology close to the limit of efficiency, in which most components have been tested and optimised over many years. However, the efficiency of many old hydropower turbines could be improved by retrofitting new equipment. Hydropower has little or no potential in the low-lying terrain of Denmark.

Wave energy can be seen as stored wind energy, and could therefore form an interesting partnership with wind energy. Waves will normally persist for six to eight hours after the wind has dropped.

The technical potential for wave power in Denmark is estimated to be able to cover one-third to two-thirds of current electricity consumption. However, this would probably require an unacceptably large area in the Danish part of the North Sea. An ambitious yet realistic goal for Danish wave power by 2050 could be around 5% of electricity consumption. Globally, the potential for wave power is at least 10% of total electricity consumption, or more if we tolerate higher prices.

Bioenergy

Biomass presently covers approximately 10% of the world's energy consumption. A realistic estimate of the total sustainable biomass potential in 2050 is 200-500 EJ/yr, covering up to half of the world's energy needs in 2050.

However, the variability of biomass production makes such a comparison simplistic. Factors to take into account include:

- future demand for food, determined by population growth and changes in diet;
- the types of food production systems that can be adopted worldwide over the next 50 years;
- productivity of forest and energy crops;
- increasing use of biomaterials;
- availability of degraded land on which to grow biomass;
- competition between different land uses, such as reforestation on surplus agricultural land;
  and
- ecological impacts.

A large proportion of biomass will probably still be in the form of wood for direct burning in less developed areas of the world. Biomass plays a special role as an easily storable form of energy, deployable in CHP systems based on sophisticated combustion technologies, and as a source of liquid fuels for transport.

Much more organic waste will be used for bioenergy in the future, solving a waste problem and recirculating nutrients to ecosystems. New forms of biomass such as algae might also contribute.

Several technologies are currently being developed with a view to improving biomass use, and these will help to make bioenergy competitive when oil prices increase. However, it is unlikely that bioenergy can provide the bulk of the world's energy. Biomass is a limited resource, and increases in biomass production should preferably not compete with food supply.

Geothermal

Geothermal energy is used in two ways: At least 24 countries produce electricity from geothermal energy, while 76 countries use geothermal energy directly for heating and cooling. In 2008, the global production of geothermal heat was 0.2 EJ, with 10 GW of installed baseload electricity production capacity.

The last two decades have seen several projects "mining" high-temperature heat by injecting cold water into hot rocks in very deep boreholes. Known variously as hot dry rocks (HDR), enhanced geothermal systems (EGS) and engineered geothermal systems (EGS), these projects have been tested in the USA, Europe and Japan.

In Denmark, the potential for geothermal energy is substantial since suitable aquifers are available, and the technology is an excellent match for the district heating systems already widely used. Geothermal energy is therefore expected to cover a large part of the demand for future district heating. The Greater Copenhagen area has enough geothermal reserves to meet all its needs for heat for thousands of years.

Heat storage in combination with geothermal energy is at an early stage of development. In future, spare heat in the summertime from sources such as solar plants and incinerators could be used to raise the temperatures of geothermal reservoirs. In winter, it would then be possible to increase the energy output of the geothermal systems.

According to estimates by the International Energy Agency, the most probable potential for the global geothermal resource is 205 EJ/yr, including 65 EJ/yr from electricity production.

Storage

To date, R&D work on energy storage has focused on electricity, probably because electricity storage has an obvious, straightforward and urgent role in the energy market. There is no doubt that many types of electricity storage will be of great importance in the coming decades.

Several different electricity storage technologies have been developed, and systems are in operation around the world, though they are not widespread. Well-known technologies typically used for fast response include stationary batteries and flywheels, while compressed air energy storage (CAES) and pumped hydropower both provide longer-term storage suitable for spot market arbitrage.

A shift to sustainable energy sources will also require mobile storage technologies for vehicles. Capturing electricity from wind and solar sources, mobile storage technologies will need to deliver driving ranges similar to those of modern gasoline and diesel vehicles.

At a first glance, batteries may seem the obvious choice to replace fossil fuels for transport, but even with today's advanced batteries, the driving range of electric vehicles falls far short of conventional vehicles. The fundamental problem is that batteries have an energy density almost two orders of magnitude lower than fossil fuels.

At some point in future, storing energy as hydrocarbons synthesised from hydrogen, made by the electrolysis of water, and carbon dioxide extracted from the atmosphere may become viable. The distribution system for liquid fuels is in place, so synthetic liquid fuels will not require huge investments in new distribution systems.

There is also considerable technical and economic potential for heat storage. Thermal energy storage technologies fall into two categories based on the physical processes involved: phase change materials (PCM) and sensible heat storage utilising the heat capacity of storage material. For both technologies effective thermal insulation is essential, particularly when used to store heat over long periods.

Huge underground heat storage reservoirs might become important for the seasonal storage of heat and cold in appropriate locations around the world, depending on geology and surface temperature variations. If such stores were large enough, their heat losses could be relatively small and therefore acceptable.

Energy storage has enormous technical potential, and it is likely to appear in many different guises among the building blocks of a future sustainable energy system. However, the costs associated with storing energy are often considerable and sometimes prohibitive.

Nuclear

Nuclear fission is a proven technology, but its exploitation has grown slowly in the past 30 years. However, the need for an energy supply with low fossil fuel dependence and low greenhouse gas emissions has led to renewed interest in nuclear energy. Many countries now plan to adopt or expand their use of nuclear fission.

The USA expects a nuclear renaissance, and China, India and Russia have even more ambitious plans for expanding nuclear power by 2030 through the installation of 100, 60 and 20 GWe, respectively.

Nuclear fusion power is a developing technology that will not be available for large-scale electricity production until the middle of the century. Compared to fission, however, the successful development of fusion energy would mean less radioactive waste and much less worry about the proliferation of nuclear weapons.

Nuclear fission reactors are used in 30 nations, predominantly in the OECD countries of North America and Europe, in south-east Asia and in the former Soviet Union. In total, nuclear fission provides 14% of the world's electricity consumption, though this figure has fallen slightly in recent years.

Based on existing plans, world nuclear capacity may therefore increase from its present 340 GWe to more than 1,000 GWe in 2050, increasing nuclear's share of the electricity supply to 20%. However, such projections are highly uncertain since they are influenced by technical, economic and especially political and social considerations.

The three existing generations of nuclear fission reactors represent an evolution of thermal neutron technology towards improved safety and economics, but with relatively minor changes to the basic concept. Generation III+ emphasises simplified designs, reducing the likelihood of system failure, and the expanded use of passive safety systems which do not rely on external power. In the next generation of nuclear energy systems known as Generation IV, reactor designs are developed for improved sustainability, meeting requirements for economics and safety while addressing concerns over proliferation and radioactive waste. The Generation IV energy systems include fast-neutron breeder reactors that employ closed fuel cycles, allowing for a much improved utilisation of uranium resources as well as a reduction of the volume of radioactive waste. The Generation IV reactors have higher operating temperatures, which opens up for new applications of nuclear energy, such as high-temperature process heat, and liquid chemical fuels and thermo-chemical hydrogen production. With sufficient progress in research and development, first-of-a-kind Generation IV reactors could be developed around 2030, with commercial deployment starting from 2040.

Fusion research is now taking the next step with the construction of a large-scale research tokamak, ITER, in France. Expected to start operating in 2020, ITER is a worldwide collaboration that will demonstrate net energy production from controlled fusion for the first time by 2026.

Building on experience gained from ITER, plans are to build the future DEMO facility in 2030-2040 and for it to operate during 2040-2050, generating several hundreds of megawatts electricity for extended periods of time. DEMO will also test and qualify key components under realistic operating conditions. If everything goes according to plan, the first commercial fusion power plant will then be in operation by 2050.

CCS

Carbon capture and storage (CCS) can be used on large point sources based on fossil fuels such as power plants and industrial furnaces. The technology can be retrofitted at existing combustion plants without major changes, but running costs are rather high.

The CO_2 produced can be stored or used in several different ways, though only ocean and geological storage have the potential to take up very large amounts. In time, CO_2 stored in the oceans will reach equilibrium with the atmosphere, so this is not a permanent disposal route. CO_2 injected into geological formations, on the other hand, is potentially stable for millions of years.

The main cost of CCS is for the CO_2 capture stage, in terms of both its capital cost and the loss in efficiency at the power plant to which it is fitted.

To improve the chances of meeting the targets for CO_2 reduction, CCS should be used worldwide, and the building of full-scale demonstration plants must be accelerated to drive down costs. Proven fossil fuel reserves, especially coal, will last far beyond this century. With CCS, we can continue to burn fossil fuels even in a carbon-neutral future. Later, CCS can even be used with biomass-fired power plants to create net negative CO_2 emissions.

Technologies for the three individual steps in CCS (capture, transport and storage) already exist, and there is enough proven geological storage capacity to allow large-scale use of CCS. However, the technology needs further development and refinement through demonstration plants.

System aspects

The energy systems of today have developed gradually over the past 100 years or more. This evolution is reflected in their structure, which is based primarily on central production units delivering electricity through transmission lines to the distribution networks and thence to end-users.

Future systems will have to be much more sophisticated, with both central and decentralised generating units closely linked to end-users through intelligent communications networks. This will take decades to achieve in industrialised nations. Intelligent energy systems could be developed more rapidly in developing countries with fast-growing economies, as these countries have to invest in a new infrastructure. As a result, intelligent energy systems could be widespread by 2050.

There is also a need for a smart grid which will link production and end-use at the local level. End-users must help to maintain balance in the future energy system. New end-use technologies have to be widely introduced, including highly insulated, almost self-sufficient houses, smart electronic equipment, energy storage and heat pumps. Information and communications technology (ICT) will be very important to the successful integration of renewables in the grid.

In the past ten years, the hydrogen economy has been discussed intensively, and among some experts there have been high expectations that hydrogen will become an alternative energy carrier for transport applications. However, experts have also for a long time been debating whether a hydrogen economy will indeed come to play a large role.

Developing the necessary infrastructure will, however, require huge investments and new technology, so it is unlikely that hydrogen will make a major contribution before the middle of this century.

District heating and cooling (DHC) grids, like their counterparts carrying natural gas, are often deemed to contribute to reducing GHGs. District heating is a flexible technology which can use any fuel or heat source, including waste energy, renewables, geothermal energy and, most significantly, heat from combined heat and power (CHP) systems. Denmark has, along with former communist countries, been at the forefront in exploiting DHC for a long time. In the long term, it seems likely that DHC will remain important, but there will be challenges following the widespread introduction of low-energy houses with a very low annual demand for heating, but not necessarily low peak demand.

Electric supergrids based on high-voltage direct current (HVDC) technology are promising because they offer the controllability needed to handle wind power effectively as well as efficient transport of electricity over long distances, even between different synchronous zones. Compared to other energy distribution systems, power grids are particularly vulnerable to disturbances and accidents. Information and communications technology (ICT) will therefore be very important to the successful integration of renewables with the grid.

High proportions of renewable energy in energy systems will also require a number of supporting technologies, including energy storage and load management, to deal with fluctuating power from renewables such as wind turbines.

Today, the welfare gains are too insignificant to motivate end-users, because in most countries the production cost of electricity is small compared to the fixed additives. Switching to percentage-type additives, grid payments which vary according to the grid load, and variable tariffs and taxes could stimulate flexible demand and "demand shifting".
Large-scale electricity storage would be able to shift demand and supply, helping to provide balance at all timescales, and may therefore be important in future intelligent power systems.

Conclusions

By 2050, the sum of the potential of all the low-carbon energy sources exceeds the expected demand. The challenge for a sustainable global energy system with low CO_2 emissions by 2050 is therefore to utilise this potential in the energy system in an economically attractive way. It will not be possible to develop the energy systems of the future simply by improving the components of existing systems. Instead, we need an integrated process that will optimise the entire system, from energy production, through conversion to an energy carrier, energy transport and distribution, and efficient end-use.

Similarly, significant reductions in primary energy consumption will not be reached through evolutionary development of existing systems. This will require paradigm shifts and revolutionary changes, such as the automatic adaptation of consumption to match the instantaneous availability of all forms of energy.

A future intelligent power system requires investment now, since uncertainty among investors is already hindering progress towards a higher share of renewable energy. If we do not make this investment, future generations may look back in disbelief that for so long we tolerated an antiquated energy system without putting in place the improvements that were already possible.

15
References

Chapter 3

- ETP, 2008. Energy Technology Perspectives 2008. Scenarios & Strategies to 2050. OECD/IEA 2008.
- ETP, 2010. Energy Technology Perspectives 2008. Scenarios & Strategies to 2050. OECD/IEA 2010.
- IPCC, 2007. Climate Change 2007. Mitigation of Climate Change. Contribution of the IPCC WIII to the Fourth Assessment. Cambridge University Press.
- Rao et al., 2008. IMAGE and MESSAGE Scenarios Limiting GHG concentration to Low Levels, Interim Report IR-08-020, IIASA Austria.
- Shukla et al., 2010. Renewable energy and low carbon economy transition in India. Journal of Renewable and Sustainable Energy 2, 1 (2010).
- USA, 2007. Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations. U.S. Climate Science Program Synthesis and Assessment Product 2.1a.

Chapter 4

- Capros, P., Antzos, L., Papandreou, V. and Tasios, N., 2008. European Energy and Transport: Trends to 2030 – Update 2007. Belgium: European Commission Directorate-General for Energy and Transport.
- EMF22, 2009. International Scenarios, Energy Economics 31, 2009.
- IEA, 2009. World Energy Outlook 2009.
- Metz, B., O.R. Davidson, P. R. Bosch, R. Dave, L.A. Meyer, editors. Climate Change 2007: Mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the International Panel on Climate Change. Cambridge: Cambridge University Press, 2007.
- Labriet, M., F. Babonneau, N. Edwards, A. Haurie, P. B. Holden, A. Kanudia, R. Loulou, J. Thénié, M. Vielle, 2010. Integrated system for the assessment of climate negotiations. Long abstract, International Energy Workshop 2010, Stockholm, Sweden, 9 p.
- Loulou, R., M. Labriet and A. Kanudia, 2009. Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes. Energy Economics, Vol. 31, Suppl. 2, Results from EMF 22, pp. S131-143.
- Loulou, R. and M. Labriet, 2008. ETSAP-TIAM: the TIMES integrated assessment model Part I: model structure. Computational Management Science, special issue "Managing Energy and the Environment", Vol. 5, Issue 1, pp. 7-40.
- Loulou, R., 2008. "ETSAP-TIAM: The TIMES integrated assessment model – Part II: mathematical formulation", Computational Management Science, special issue on Energy and Environment, Vol. 5, No. 1-2, pp. 41-66.

Chapter 5

1. Technology Roadmap – Solar photovoltaic energy (2010). International Energy Agency, www.iea.org.
2. PikeResearch, Global Solar Energy Outlook, 2010, www.pikeresearch.com.
3. U.S. Geological Survey, MINERAL COMMODITY SUMMARIES 2007.
4. Nielsen, T.D.; Cruickshank C.; Foged S.,Thorsen, J.; Krebs, F.C. (2010). Business, market and intellectual property analysis of polymer solar cells. Solar Energy Materials and Solar Cells, 94(10), 1553-1571.
5. Krebs, F.C.; Fyenbo, J.; Jørgensen, M. (2010). Product integration of compact roll-to-roll processed polymer solar cell modules: methods and manufacture using flexographic printing, slot-die coating and rotary screen printing. J. Mater. Chem., 2010, Advance Article DOI:10.1039/C0JM01178A.
6. W. G. J. H. M. van Sark, E. A. Alsema, H. M. Junginger, H. H. C. de Moor and G. J. Schaeffer, Progr. Photovolt.: Res. Appl., 2008, 16, 441-453. Data augmented with EPIA numbers.
7. F. C. Krebs, S. A. Gevorgyan, J. Alstrup and J. Mater. Chem., 2009, 19, 5442-5451.
8. Technology Roadmap – Concentrating Solar Power (2010). International Energy Agency, www.iea.org.
9. www.desertec.org; www. dii-eumena.com.
10. Pitz-Paal, R.; Dersch, J.; Milow, B.; Téllez, F.; Ferriere, A.; Langnickel, U.; Steinfeld, A.; Karni, J.; Zarza, E.; Popel, O. (2005). Development steps for concentrating solar power technologies with maximum impact on cost reduction. In International Solar Energy Conference (ISEC-2005) proceedings, Orlando (Fl, USA), August 2005.
11. Mikkelsen, M.; Jørgensen, M.; Krebs, F. C. (2010). Energy & Environmental Science 3, 43-81.
12. Ahm, P. (2010). National Survey Report of PV Power Applications in Denmark, IEA co-operative programme on photovoltaic power systems (www.IEA-PVPS.org).

Chapter 6

1. Global Wind Energy Outlook 2008, GWEC.
2. Nitsch, F. (2007). Technologische und energiewirtschaftliche Perspektiven erneuerbarer Energien, DLR.
3. Lemming, J., Morthorst, P.E., Clausen, N.E., Jensen, P.H., Contribution to the Chapter on Wind Power Energy Technology Perspectives 2008, Risø report, Risø-R-1674(EN), Jan. 2008.
4. Archer, C. L. and M. Z. Jacobson (2005). Evaluation of global wind power, J. Geophys. Res., 110, D12110, doi:10.1029/2004JD005462.

5. REN21. 2008. "Renewable Energy Potentials in Large Economies – Summary Report" (Paris: REN21 Secretariat).
6. International Wind Energy Development, World Market Update 2009, Forecast 2010-2014, BTM-Consult, March 2010.
7. Ashwill 2008.
8. Archer, C.L. and Caldeira, K., Global Assessment of High-altitude Wind Power, Energies 2009, pp. 307-319.
9. Shimon Awerbuch, Determining the real cost – Why renewable is more cost-competitive than previously believed, Renewable Energy World, March-April 2003.
10. Wind Force 12, A blueprint to achieve 12% of the world's electricity from wind power by 2020, European Wind Energy Association & Greenpeace, May 2003.

Chapter 7

- Bahaj, A.S., 2009. "The status of tidal stream energy conversion", in IEA-Ocean Energy Systems annual report 2008.
- Baras, C. (2010). "Will the anaconda or the oyster rule wave power?" New Scientist, 6 March 2010.
- Falcão, A.F. (2009). "The development of wave energy utilization", in IEA-Ocean Energy Systems annual report 2008.
- IEA, 2008: World Energy Outlook 2008. International Energy Agency, France.
- Kofoed, J. P. and Frigaard, P.: Development of wave energy devices: the Danish case. The Journal of Ocean Technology, vol. 4, no. 4, Dec. 2009.
- G. Mørk, S. Barstow, A. Kabuth and M. T. Pontes: Assessing the Global Wave Energy Potential, Proceedings of the ASME 2010 29th Int. Conf. on Ocean, Offshore and Arctic Engineering, Shanghai, China, 2010.
- Ngô, C., Lescure, I., Chanpvillard, G. (2006). Energy from the sea, EUSTEL European Sustainable Electricity.
- Nihous, G.C. (2009). "Ocean Thermal Energy Conversion (OTEC) and derivative technologies: status of development and prospects", in IEA-Ocean Energy Systems annual report 2008.
- Scråmestø, O.S., Skilhagen, S.E., 2009. "Status of technologies for harnessing salinity power and the current osmotic power activities", in IEA-Ocean Energy Systems annual report 2008.
- Sørensen, H. C. and Weinstein, A.: Ocean Energy: Position paper for IPCC. Key Note Paper for the IPCC Scoping Conference on Renewable Energy, Lübeck, Germany, January 2008.
- UNWWAP, 2006 Water – A shared Responsibility Book. United Nations World Water Assessment Programme.
- WaveStar 2010. www.wavestarenergy.com.
- WCD, 2000: Dams and Development – A new framework for decision-making, UK.

Chapter 8

- Blume, S., Hauggaard-Nielsen, H. and Jensen, E.S., 2008 Opgørelse af den danske biomasseressource til brug for fremstilling af biobrændstoffer til transportsektoren frem mod 2020. Risø-R-1665(DA), National Laboratory for Sustainable Energy, Technical University of Denmark.
- Christi, Y. (2007). Biodiesel from microalgae. Biotechnol. Adv. 25, 294-306.
- Dam JV, Junginger M, Faaij A, Jurgens I, Best G, Fritsche U, 2008. Overview of recent developments in sustainable biomass certification. Biomass and Bioenergy 32, 749-780.
- Dornburg V, van Vuuren D, van de Ven G, Langeveld H, Meeusen M, Banse M, van Oorschot M, Ros J, van den Born GJ, Aiking H, Londo M, Mozaffarian H, Verweij P, Lyseng E and Faaij A, 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy & Environmental Science 3, 258-267.
- EEA, 2006. How much bioenergy can Europe produce without harming the environment? EEA Report No. 7. European Environment Agency.
- EU, 2009: Directive 2009/28/EC of 23 April 2009 on renewable energy, OJ L 140/28, 05.06.2009.
- European Commission, 2010: Biofuels: Sustainability Criteria, http://ec.europa.eu/energy/renewables/biofuels/sustainability_criteria_en.htm
- Faaij A, 2008. Developments in international bio-energy markets and trade. Biomass and Bioenergy 32, 657-659.
- FAO, 2008. Bioenergy, food security and sustainability – towards an international framework. Background document for High-level Conference on World Food Security: the Challenges of Climate Change and Bioenergy. Rome, 3-5 June 2008, www.fao.org/foodclimate.
- FAO, 1998. Biodiversity for maintenance of agro-ecosystem functions, www.fao.org/biodiversity.
- Hoogwijk M, Faaija A, van den Broek R, Berndesb G, Gielenc D and Turkenburg W, 2003. Exploration of the ranges of the global potential of biomass for energy. Biomass and Bioenergy 25, 119-133.
- IEA, 2009. Key World Energy Statistics. Published by the International Energy Agency, 9, rue de la Fédération, 75739 Paris Cedex 15, France. 82 pp.
- IEA, 2007. Annual Report 2007 – IEA Bioenergy. Editor: John Tustin. 120 pp. IEA Bioenergy Secretariat, Rotorua, New Zealand. www.ieabioenergy.com.
- IEA BIOENERGY: Bioenergy – a Sustainable and Reliable Energy Source. MAIN REPORT. IEA BIOENERGY: ExCo: 2009:06.
- Jacobson, M.Z., 2009. Review of solution to global warming, air pollution and energy security. Energy Environ. Sci. 2, 148-173.

- Ladanai S and Vinterbäck J, 2009. Global Potential of Sustainable Biomass for Energy. Swedish University of Agricultural Sciences, Department of Energy and Technology, Uppsala, Sweden. 32 pp. Report 013, ISSN 1654-9406.
- Smeets EMV, Faaij APC, Lewandowski IM, Turkenburg WC, 2007. A bottom-up assessment and review of global bioenergy potentials to 2050. Progress in Energy and Combustion Science 33, 56-106.
- Spolaore P., Joannis-Cassan C, Duran E, Isambert A (2006). Commercial application of microalgae. J Biosci Bioeng; 101:87-96.
- Zah, R et al., 2007. LIFE CYCLE ASSESSMENT OF ENERGY PRODUCTS: ENVIRONMENTAL ASSESSMENT OF BIOFUELS. Empa Technology and Society Lab. Switzerland.
- Østergaard H, Finckh MR, Fontaine L, Goldringer I, Hoad SP, Kristensen K, van Bueren ETL, Mascher F, Munk L and Wolfe MS 2009. Time for a shift in crop production: embracing complexity through diversity at all levels. Journal of the Science of Food and Agriculture 89, 1439-1445.

Chapter 9

- Bertani, R. (2007). Long-term projections of geothermal-electric development in the world. www.iea-gia.org/documents/LongTermGeothermElecDevelopWorldBertanioffenburg23Feb09.pdf.
- Magtengaard, J., Mahler, A.: Geothermal reserves and sustainability in the Greater Copenhagen Area, DONG Energy, proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.
- ENERDATA (2010). globaldata.enerdata.eu..
- Danish Energy Agency: Geotermi – varme fra jordens indre. Internationale erfaringer, økonomiske forhold og udfordringer for geothermisk varmeproduktion i Danmark, May 2010.
- Holm, A., Blodgett, D.J., Gawell, K., Geothermal Energy: International Market Update. Geothermal Energy Association (GEA), May 2010. http://www.geo-energy.org/pdf/reports/GEA_International_Market_Report_Final_May_2010.pdf.
- Goldstein, B.A., Hill, A.J., Budd, A.R., Holgate, F., Malavazos, M. (2008). Hot Rocks Downunder – Geothermal Plays in Australia. www.searchanddiscovery.net/documents/2008/08181goldstein/goldstein-80015.pdf.
- Lippmann, M.J. (2002). Geothermal and the Electricity Market in Central America. Geothermal Resources Transactions 26, 37-42.
- Mathiesen, A., Kristensen, K., Bidstrup, T. & Nielsen, L.H., 2009: Vurdering af det geotermiske potentiale i Danmark. Geological Survey of Denmark and Greenland Report 2009/59. 30 pp., 23 figs. http://www.geus.dk/program-areas/energy/denmark/geus_rap_2009_59-dk.htm.
- MIT (2007): The Future of Geothermal Energy – Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century.
- Nielsen, L.H., Mathiesen, A. & Bidstrup, T., 2004: Geothermal energy in Denmark. Review of Survey Activities 2003. Geological Survey of Denmark and Greenland bulletin 4, 17-20. http://www.geus.dk/publications/bull/nr4/nr4_p17-20-dk.htm.
- Soultz (2009). www.soultz.net. The European Hot Dry Rock Project.
- Stephure T. (2009). Geothermal Development Expands Globally. EnergyPulse, 13 May 2009. www.energypulse.net/centers/article/article_display.cfm?a_id=2037.
- The Economist, Technology Quarterly: Hot rocks and high hopes, 4 September 2010.

Chapter 10

- D. Mangold, T. Schmidt. The Next Generations of Seasonal Thermal Energy Storage in Germany, ESTEC 2007, European Solar Thermal Energy Conference, Freiburg 2007.
- B. Zalba, J. Marín, L. Cabeza, H. Mehling. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications, Applied Thermal Engineering 27, 1271-1277 (2007).
- Varmeplan hovedstaden 2009. Baggrundsrapport om teknologier.
- S. Succar, R. H. Williams. Compressed Air Energy Storage: Theory, Resources, And Applications For Wind Power, CAES Report, Princeton University 2008.
- C. Ekman, S.H. Jensen. Prospects for Large Scale Electricity Storage in Denmark, Energy Conversion and Management 51, 1140-1147 (2010).
- Greenpeace/EREC, 2008. Energy [R]evolution 2008 – a sustainable world energy outlook. Published by Greenpeace International and the European Renewable Energy Council (EREC), www.energyblueprint.info.
- Solar Heating and Cooling for a Sustainable Energy Future in Europe, European Solar Thermal Technology Platform (ESTTP), esttp.org/cms/upload/SRA/ESTTP_SRA_RevisedVersion.pdf

Chapter 11

1. http://europa.eu/legislation_summaries/energy/european_energy_policy/l27069_en.htm.
2. Nuclear Energy Outlook 2008, OECD/NEA; Energy Technology Perspectives 2050, IEA.
3. MIT, The Future of Nuclear Power, 2009 Update.

4. Sustainable Nuclear Energy Technology Platform, SNETP, www.snetp.eu.
5. "History and Evolution of Fusion Power Plant Studies: Past, Present and Future Prospects", Chapter 6 in "Nuclear Reactor, Nuclear Fusion and Fusion Engineering", NOVA Science Publishers Inc., pp. 217-271 (2009).
6. www.jet.efda.org/jet/.
7. www.iter.org.
8. https://lasers.llnl.gov.
9. "History and Evolution of Fusion Power Plant Studies: Past, Present and Future Prospects", Chapter 6 in "Nuclear Reactor, Nuclear Fusion and Fusion Engineering", NOVA Science Publishers Inc., pp. 217-271 (2009).

Chapter 12

1. International Energy Agency. Energy Technology Perspectives 2008 – Scenarios and Strategies to 2050. 2008.
2. Global CCS Institute. Strategic Analysis of the Global Status of Carbon Capture and Storage, Report 5, Synthesis Report. 2009.
3. Metz, B., O. Davidson, H. C. de Coninck, M. Loos and L. A. Meyer (eds.). IPCC Special Report on Carbon Dioxide Capture and Storage. Cambridge University, 2005.
4. Pöyry. Carbon Capture and Storage: Milestones to Deliver Large Scale Deployment by 2030 in the UK. 2009.
5. Anthonsen, K. L., F. Dalhoff, N. P. Christensen, M. Larsen. EU GeoCapacity Denmark. Geus, 2009.
6. Bradshaw, J., S. Bachu, D. Bonijoly, R. Burruss, S. Holloway, N. P. Christensen and O. M. Mathiassen. CO_2 storage capacity estimation: Issues and development of standards. International Journal of Greenhouse Gas Control. 2007.
7. Vangkilde-Pedersen, T., K. L. Anthonsen, N. Smith, K. Kirk, F. Neele, B. van der Meer, Y. Le Gallo, D. Bossie-Codreanu, A. Wojcicki, Y.M. Le Nindre , C. Hendriks, F. Dalhoff and N. P. Christensen. Assessing European capacity for geological storage of carbon dioxide – the EU GeoCapacity project. Energy Procedia, 2009.
8. EU GeoCapacity. Assessing European capacity for geological storage of carbon dioxide. WP 2 Report, 2009.
9. McKinsey & Co., Carbon Capture & Storage: Assessing the Economics. 2008.
10. International Energy Agency. Technology Roadmap – Carbon capture and storage. 2009.

Chapter 13

1. International Energy Agency (2009). World Energy Outlook 2009, Paris: OECD/IEA.
2. District Heating & Cooling, A Vision Towards 2020-2030-2050, DHC+ Technology Platform.
3. http://ewea.org/fileadmin/ewea_documents/documents/publications/reports/Offshore_Report_2009.pdf.
4. The Intelligent Energy System for Tomorrow. Hans Larsen, Poul Erik Morthorst, Henrik Bindslev and Leif Sønderberg Petersen, Risø National Laboratory for Sustainable Energy, the Technical University of Denmark. WEC, Montreal, September 2010.
5. Political declaration on the North Seas Countries Offshore Grid Initiative: www.ewea.org/fileadmin/ewea_documents/documents/policy/Offshore_Wind/Political_declaration_on_the_North_Seas_Countries_Offshore_Grid_Initiative.pdf.
6. http://ewea.org/fileadmin/ewea_documents/documents/publications/reports/Offshore_Report_2009.pdf.
7. Kofod, C.; Togeby, M. (2004). Demand response offered by households with direct electric heating. Demand response in energy markets, Conference proceedings, Nordic Energy Research, 26 November 2004. Oslo: Nordic Energy Research.
8. Andersen, F.M.; Jensen, S.G.; Larsen, H.V.; Meibom, P.; Ravn, H.; Skytte, K.; Togeby, M. (2006). Analyses of demand response in Denmark. (Risø-R-1565(EN)). Roskilde: Risø National Laboratory.
9. U.S. DoE. (2006). Benefits of demand response in electricity markets and recommendations for achieving them. A report to the United States Congress pursuant to section 1252 of the Energy Policy Act of 2005. U.S. Washington, DC: Department of Energy. http://eetd.lbl.gov/ea/EMP/reports/congress-1252d.pdf (26 July 2009).
10. The Intelligent Energy System Infrastructure for the Future. Risø Energy Report 8. Hans Larsen and Leif Sønderberg Petersen (eds), Risø-R-1695(EN), 2008.

16
Index

17
Risø Energy Report Series

Risø Energy Report 1
New and emerging technologies: options for the future

All over the world, increasing energy consumption, the liberalisation of energy markets and the need to take action on climate change are producing new challenges for the energy sector. At the same time, there is increasing pressure for research, new technology and industrial products to be socially acceptable and to generate prosperity. The result is a complex and dynamic set of conditions affecting decisions on investment in research and new energy technology.
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø National Laboratory, October 2002, 64 pp., ISBN 87-550-3082-3, Risø-R-1351(EN)

Risø Energy Report 2
New and emerging bioenergy technologies

Three growing concerns – sustainability (particularly in the transport sector), security of energy supply and climate change – have combined to increase interest in bioenergy. This trend has been further encouraged by technological advances in biomass conversion and significant changes in energy markets. We even have a new term, "modern bioenergy", to cover those areas of bioenergy technology – traditional as well as emerging – which could expand the role of bioenergy.
Edited by Hans Larsen, Jens Kossmann and Leif Sønderberg Petersen
Risø National Laboratory, November 2003, 48 pp., ISBN 87-550-3262-1, Risø-R-1430(EN)

Risø Energy Report 3
Hydrogen and its competitors

Interest in the hydrogen economy has grown rapidly in recent years. Countries with long traditions of activity in hydrogen research and development have now been joined by a large number of newcomers. The main reason for this surge of interest is that the hydrogen economy may be an answer to the two main challenges facing the world in the years to come: climate change and the need for security of energy supplies. Both these challenges require the development of new, highly efficient energy technologies that are either carbon-neutral or low-carbon.
Edited by Hans Larsen, Robert Feidenhans'l and Leif Sønderberg Petersen
Risø National Laboratory, October 2004, 76 pp., ISBN 87-550-3350-4, Risø-R-1469(EN)

Risø Energy Report 4
The future energy system: distributed production and use

The coming decades will bring big changes in energy systems throughout the world. These systems are expected to change from central power plants producing electricity and sometimes heat for customers, to a combination of central units and a variety of distributed units such as renewable energy systems and fuel cells.
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø National Laboratory, October 2005, 62 pp., ISBN 87-550-3474-8, Risø-R-1534(EN)

Risø Energy Report 5
Renewable energy for power and transport

Global energy policy today is dominated by three concerns: security of supply, climate change and energy for development and poverty alleviation. This is the starting point for Risø Energy Report 5, which addresses trends in renewable energy and gives an overview of the global forces that will transform our energy systems in the light of security of supply, climate change and economic growth. The report discusses the status of, and trends in, renewable energy technologies for broader applications in off-grid power production (and heat).
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø National Laboratory, November 2006, 72 pp., ISBN 87-550-3515-9, Risø-R-1557(EN)

Risø Energy Report 6
Future options for energy technologies

Fossil fuels provide about 80% of global energy demand, and this will continue to be the situation for decades to come. In the European Community, we are facing two major energy challenges. The first is sustainability, and the second is security of supply, since Europe is becoming more dependent on imported fuels. These challenges are the starting point for the present Risø Energy Report 6.
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø National Laboratory, November 2007, 84 pp., ISBN 978-87-550-3611-6, Risø-R-1621(EN)

Risø Energy Report 7
Future low-carbon energy systems

The report presents state-of-the-art and development perspectives for energy supply technologies, new energy systems, end-use energy efficiency improvements and new policy measures. It also includes estimates of the CO_2 reduction potentials for different technologies. The technologies are characterised with regard to their ability to contribute either to ensuring a peak in CO_2 emissions within 10-15 years, or to long-term CO_2 reductions. The report outlines the current and likely future composition of energy systems in Denmark and examines three groups of countries: i) Europe and the other OECD member nations; ii) large and rapidly growing developing economies, notably India and China; iii) typical least developed countries, such as many African nations. The report emphasises how future energy

developments and systems might be composed in these three country groupings, and to what extent the different technologies might contribute.
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø DTU, October 2008, 86 pp., ISBN 978-87-550-3690-1, Risø-R-1651(EN)

Risø Energy Report 8

The intelligent energy system infrastructure for the future

The report takes its point of reference in the need for the development of a highly flexible and intelligent energy system infrastructure which facilitates the integration of substantially higher amounts of renewable energy than today's energy systems. This intelligent and flexible infrastructure is a prerequisite for achieving the goals set up by IPCC in 2007 on CO_2 reductions as well as ensuring the future security of energy supply in all regions of the world.
The report presents a generic approach to future infrastructural issues on a local, regional and global scale with focus on the energy system.
The report is based on chapters and updates from Risø Energy Reports 1-7, as well as input from contributors to the DTU Climate Change Technology workshops and available international literature and reports.
Edited by Hans Larsen and Leif Sønderberg Petersen
Risø DTU, September 2009, 72 pp., ISBN 978-87-550-3755-7, Risø-R-1695(EN)